APPENDIX M

EXISTING MULTIPLE-PURPOSE SYSTEMS IN THE UNITED STATES

M-1. Introduction.

a. This appendix briefly describes seven of the major reservoir systems in the United States which include hydropower as a major function. These systems are:

- Cumberland River System
- Tennessee River System
- Arkansas River System
- Missouri River System
- Colorado River System
- Central Valley Project
- Columbia River System

This appendix illustrates the role that hydropower plays in different systems and some of the ways in which the power operation has been adapted to coexist with other operating objectives. These operating descriptions are intended to provide only a general overview of the respective system operations. For detailed information, the agency responsible for management of the system should be contacted.

b. The description of the operation of each system includes a table listing the operating characteristics of the projects in that system. The reservoir function listings generally include all existing functions, not just those included in the project authorizing legislation. For example, many projects were authorized before recreation was recognized as a Federal project function, but recreation has since developed into an important reservoir use at most of these projects. Unless otherwise noted, the tables list the project's conservation storage capacity, which usually represents the storage that can be used for power generation. This includes multiple-use conservation storage, exclusive power storage, and joint-use flood control/conservation storage, but does not include exclusive flood control storage. The installed capacity noted on the tables is the nameplate capacity of all generating units at the projects.

M-2. Cumberland River Basin System.

a. General.

(1) The Cumberland River is a tributary of the Ohio River, which runs in a general east-to-west direction, straddling the Kentucky-Tennessee border. Runoff, which is primarily from rainfall, is heaviest in the winter and spring months (Figure M-1). The Cumberland River is controlled by a multiple-purpose reservoir system consisting of five storage projects and four run-of-river navigation projects, all with power (Table M-1 and Figure M-2). The system was constructed by the Corps of Engineers, and the functions served by the projects include flood control, navigation, hydropower, and recreation.

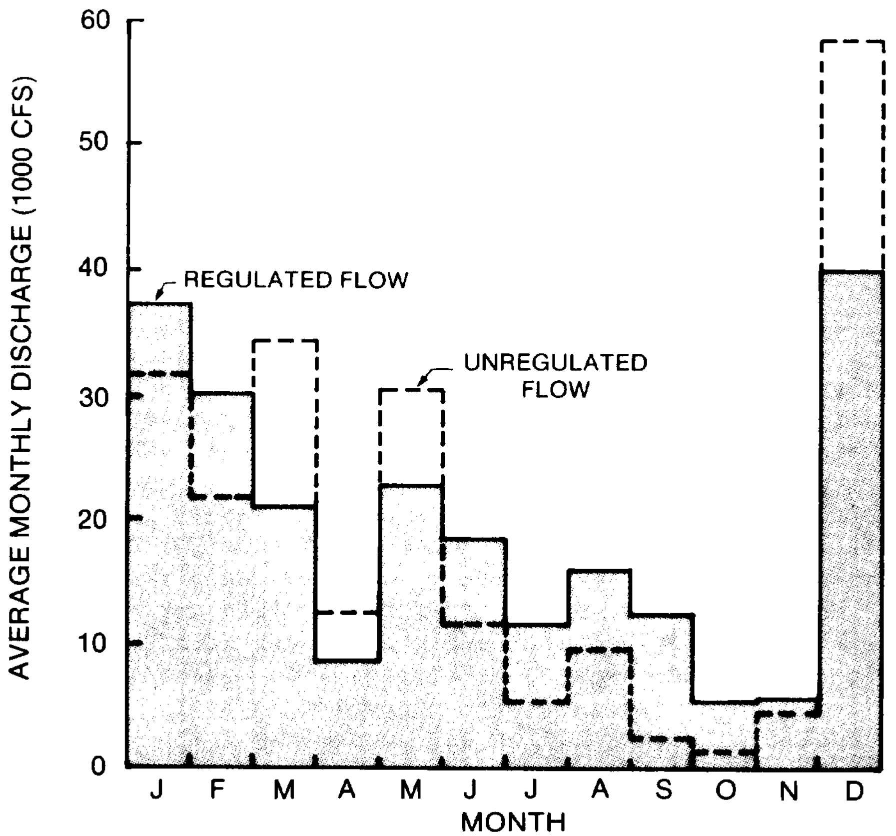

Figure M-1. Average monthly discharge of the Cumberland River at Old Hickory Dam, regulated and unregulated, for a typical year (1978)

(2) Power produced by the projects is marketed by the Southeastern Power Administration (SEPA). Prior to 1984, the power was marketed primarily to the Tennessee Valley Authority (TVA), and the Cumberland River powerplants were operated as part of the TVA system. Since that date, a large portion of the capacity has been marketed to preference customers outside of the TVA service area, and the power operating criteria of the Cumberland projects have been modified to accomodate the requirements of the outside-TVA customers.

b. System Operation.

(1) The primary functions of the Cumberland system are flood control, navigation, and hydropower. The storage projects are regulated primarily for flood control and hydropower, and releases for power generation are generally sufficient to meet the instream flow requirements for navigation and other river uses. Reservoir recreation is heavy at these projects, and efforts are made to maintain the reservoirs as high as practicable during the summer months, within the constraints of power requirements. At J. Percy Priest and Cordell Hull, the authorizing legislation specifies that summer pool elevations be maintained for recreation.

(2) Three of the five storage projects in the system provide the bulk of the control: Wolf Creek, Dale Hollow, and Center Hill. Laurel, the project that is furthest upstream, has power storage only and, since its output goes to a single customer, it is operated independently from the rest of the system. J. Percy Priest is located on the outskirts of Nashville, and its primary functions include flood control, hydropower, and recreation. The project operates in accordance with a fixed seasonal rule curve designed to keep the reservoir elevation high in the summer for recreation and low in the winter for flood control. Power generation is limited to what can be produced within these operating constraints, with most of the generation being produced in the winter and spring months.

(3) At Wolf Creek, Dale Hollow, and Center Hill, the storage is divided into two zones: an exclusive flood control zone on top and a conservation (power) storage zone on the bottom (Figure M-3). Because of the risk of large floods occurring at any time during the winter and the spring refill season, joint-use storage for both flood control and power is not practical. Regulation of the power storage follows a seasonal pattern, beginning with the reservoirs near the top of the power pool about the first of June. Storage is then gradually drafted through the low flow, high demand summer season, and the reservoir is usually at its lowest level in the late fall and early winter months. Refill takes place during the late winter and spring months.

TABLE M-1
Major Hydropower Projects in the Cumberland
River Multiple-Purpose Reservoir System

Dam	River	Owner or Operator	Reservoir Functions	Conservation Storage (1000 AF)	Installed Capacity (MW)
Laurel	Laurel	Corps	PR 1/	185	61
Wolf Creek	Cumberland	Corps	FPR	2,142	270
Dale Hollow	Obey	Corps	FPR	496	54
Cordell Hull	Cumberland	Corps	NPR	pondage	100
Center Hill	Caney Fork	Corps	FPR	492	135
Old Hickory	Cumberland	Corps	NPR	pondage	100
J. Percy Priest	Stones	Corps	FPRW	124	28
Cheatham	Cumberland	Corps	NPR	pondage	36
Barkley	Cumberland	Corps	FNPR	259 2/	130
Totals				3,698	914

1/ reservoir purposes:
F - flood control
I - irrigation
N - navigation
P - hydropower
R - recreation
W - fish and wildlife
S - water supply

2/ storage between normal full pool and winter flood control pool

(4) Figure M-3 also shows the regulation of Wolf Creek in a representative year (1978). The calendar year began with the reservoir relatively high, due to higher than average inflow in the preceding months. Some drafts were made in January and February, but they were partially offset by a storm in late January. Refill began in March, with most of the refill occurring in March and May. In late May, a storm caused the reservoir to rise into the flood control zone for a short time. Substantial drafts were made from June through November to meet power requirements, but a storm in early December refilled a large portion of the power storage. Drafting for power generation resumed shortly thereafter. Figure M-1 shows the effect of this regulation on the monthly average flow pattern.

(5) Like TVA's main river projects (Section M-3d), Barkley has a seasonally varying flood control pool with a rule curve similar to that shown for Chickamauga (Figure M-8). Within the limits imposed by the flood control rule curve, Barkley operates basically as a run-of-river project with pondage. Barkley Reservoir is connected to Kentucky Reservoir via an open canal, and the two projects are operated in unison.

(6) Because the Cumberland River system consists of multiple storage projects with downstream run-of-river projects, the power storage must be regulated as a system in order to maximize generation at both the reservoir powerplants and the run-of-river projects. Since the three main storage projects are situated in an essentially parallel configuration (Chapter 5, Section 5-14f, Case 2), storage is drafted proportionately; i.e., all of the reservoirs are maintained at approximately the same percent of power storage remaining. Variations in inflow patterns among the projects do cause some deviation from this objective, however.

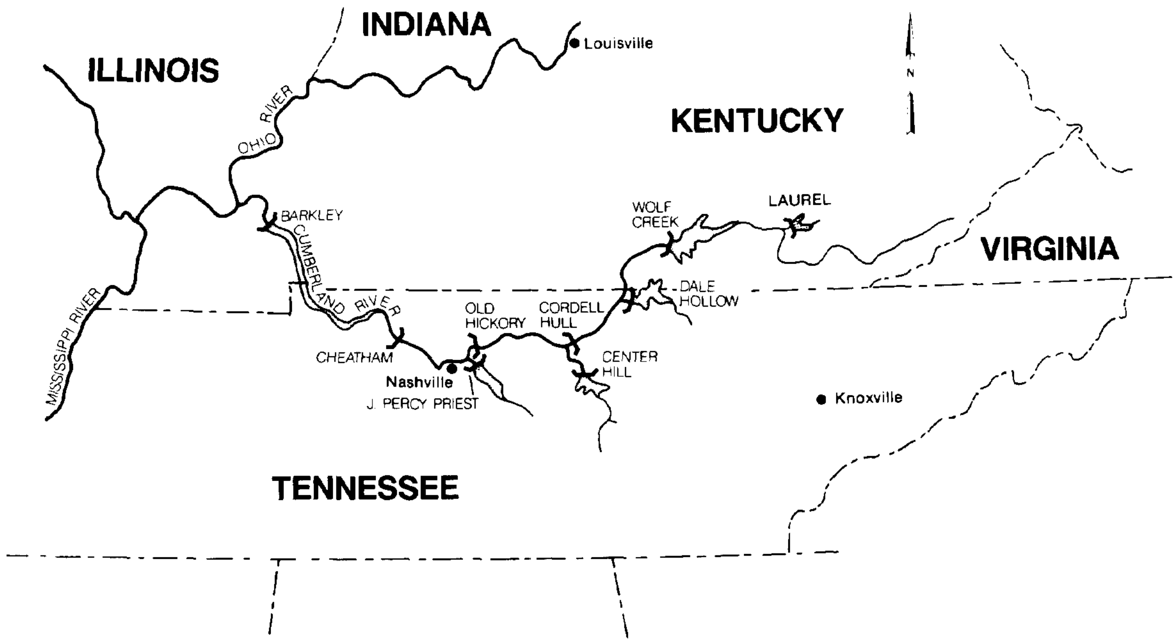

Figure M-2. Projects of the Cumberland River system

(7) The power from the Cumberland River system is marketed primarily as peaking power, so the powerplants at the storage project are operated at intermediate and peaking plant factors, except when high inflows and/or evacuation of flood control storage space permits higher generation levels. At the run-of-river projects, some pondage is provided to permit peaking operation, although this pondage is reduced or eliminated during the flood season by the need to provide surcharge space to replace lost valley storage. Minimum flows and maximum rate-of-change requirements are imposed at some projects in order to protect navigation.

c. <u>SEPA Rule Curve Operation.</u>

(1) Prior to 1984, the Cumberland River powerplants were generally dispatched as a part of the TVA system. Since 1984, a portion of the capacity has been marketed to outside-TVA customers. This in turn resulted in a new contract between TVA and SEPA, which imposed somewhat stricter operating constraints on the system. As a

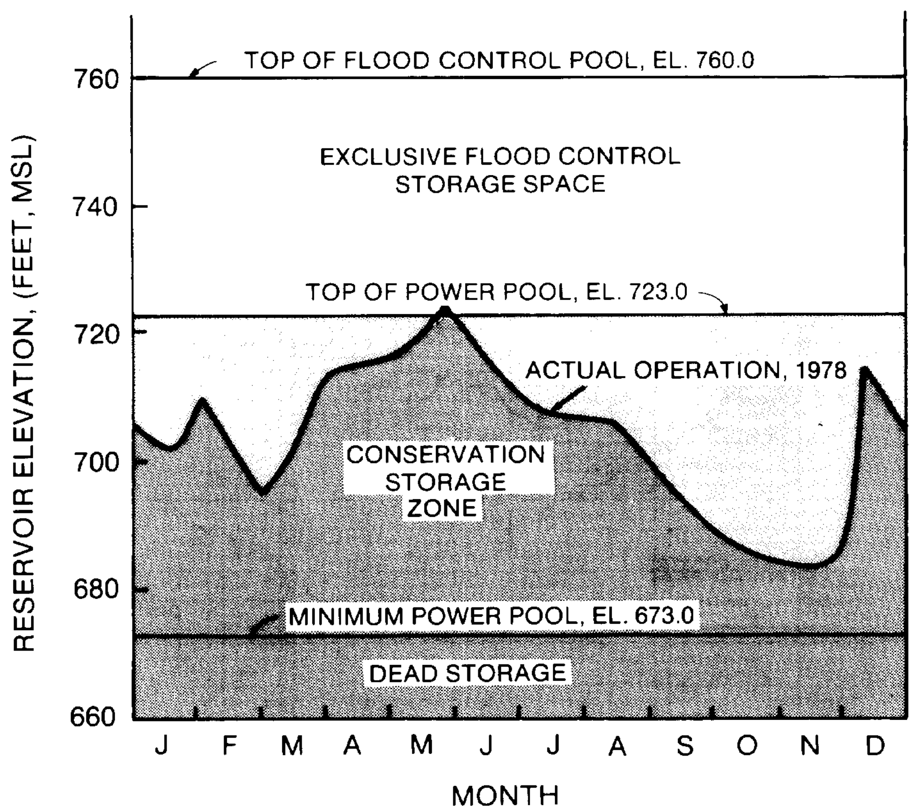

Figure M-3. Storage allocation at Wolf Creek Reservoir, showing actual operation in 1978 part of this contract, SEPA developed rule curves to define more specifically the seasonal regulation of the storage projects (Figure M-4). The power storage in each reservoir is subdivided into three zones. These zones are defined by two seasonally varying curves: the SEPA Rule Curve and the Bottom Operating Curve. The two curves are based primarily on the normal range of operation that has been experienced at the project, with some adjustments to protect capacity and to accomodate the requirements of the outside-TVA customers.

(2) As far as the outside-TVA customers are concerned, the operating objective is to meet specified weekly energy and capacity requirements. This type of operation would suggest operating against a single rule curve based on firm energy requirements. TVA prefers to use its share on more of a discretionary basis, with the amount of power used at any given time being a function of the needs of their system at that time. The use of two rule curves defining a zone of normal operation meets the requirements of both entities. The rule

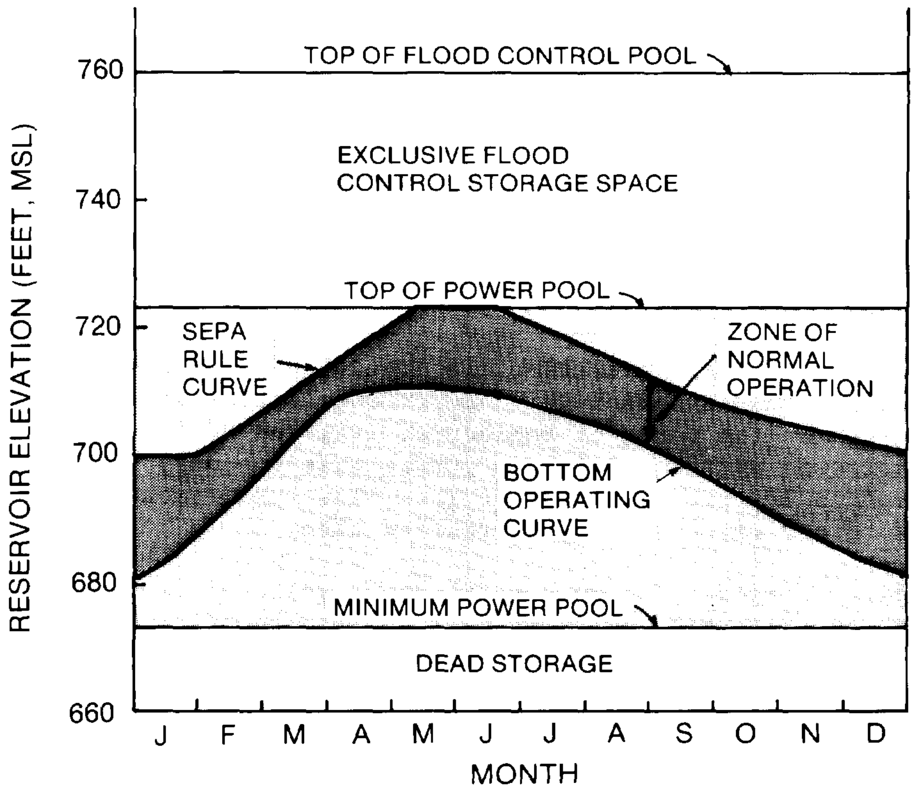

Figure M-4. Power rule curves for Wolf Creek Reservoir curves protect the weekly energy and capacity requirements of the outside-TVA customers, while the zone of normal operation permits TVA some flexibility in day-to-day operations.

(3) Typically, the projects are operated in the upper portion of the zone of normal operation. If TVA has the need for additional power, due to forced outages or unusually high loads, it may draft below this level. Later, if conditions permit, TVA may reduce its demands to permit the reservoir to approach the SEPA rule curve once again. During periods of high runoff, the reservoir may fill above the SEPA Rule Curve. In such cases, discharges will usually be increased above firm requirements in an effort to draw the reservoir back to the rule curve. If the reservoir fills into the flood control zone, that zone will be evacuated as soon as possible without violating bankfull conditions downstream, and the powerplant may be operated at full discharge, and supplemented by spill if necessary.

(4) Drafts below the Bottom Operating Curve would occur under unusually severe power situations, but any energy "borrowed" from below the zone of normal operation must be restored as soon as possible. The Bottom Operating Curve represents the minimum elevations required to insure that reservoirs will have sufficient remaining storage to meet future energy requirements.

(5) Deviations from the SEPA Rule Curve are permitted during the refill season. In a dry spring, the reservoir would be allowed to exceed the rule curve elevation in order to improve the probability of refill. In a wet spring, deviations below the rule curve might be permitted to reduce the liklihood of the reservoir filling into the flood control zone.

(6) Drafts for power generation are scheduled on a weekly basis, and the implementation of this operation requires daily coordination between the Corps of Engineers, TVA, and SEPA. The schedule of releases must be tested to insure that not only firm power requirements are met, but that minimum flow requirements for navigation and other river uses are satisfied also.

d. Critical Period. The Cumberland River reservoir system is operated on an annual cycle, with the critical period being defined as the eight-month sequence, May 1980 through January 1981.

e. Management of the System. The Cumberland River system is operated by the Nashville District, Corps of Engineers, PO Box 1070, Nashville, TN 37202. The power operation is closely coordinated with TVA and SEPA.

f. Summary. The reservoir storage in the Cumberland River system is divided into exclusive flood control and conservation storage zones. The conservation storage is regulated primarily for power on an annual cycle following rule curves. Releases for power generation are normally sufficient to meet navigation and other instream flow requirements. With the exception of Laurel, the projects are operated as a system.

M-3. Tennessee River System.

a. General.

(1) The Tennessee River drains about 41,000 square miles of seven southeastern states. Rainfall averages 52 inches over the basin and is well-distributed throughout the year. Average annual snowfall is eight inches, but it does not create a snowpack and is therefore not a significant factor in system operations. Average flow of the Tennessee River at its mouth is about 66,000 cfs. Figure M-5 shows the seasonal distribution of this flow.

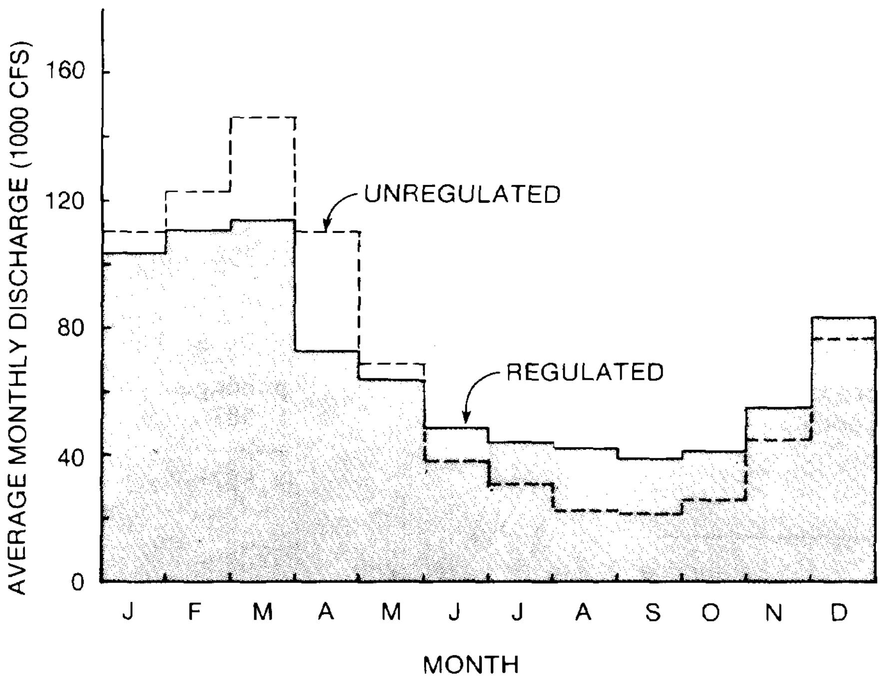

Figure M-5. Average monthly discharge of the Tennessee River at Kentucky Dam, regulated and unregulated, 1953-1980

TABLE M-2
Major Hydropower Projects in the Tennessee River Basin 2/

Project	River	Project Function 1/	Conservation Storage (1000 AF)	Installed Capacity (MW)
		Main River Projects		
Kentucky	Tennessee	FNP	721 3/	175
Pickwick Landing	"	FNP	239 3/	224
Wilson	"	NP	pondage	630
Wheeler	"	FNP	328 3/	375
Guntersville	"	FNP	132 3/	115
Nickajack	"	NP	pondage	104
Chickamauga	"	FNP	221 3/	120
Watts Bar	"	FNP	214 3/	167
Fort Loudon	"	FNP	79 3/	139
	Major Tributary Storage Projects			
Hiwassee	Hiwassee	FNP	306	117
Norris	Clinch	FNP	1,922	101
Fontana	Little Tenn.	FNP	946	239
Douglas	French Broad	FNP	1,252	121
Cherokee	Holston	FNP	1,148	135
South Holston	S. Fork Holston	FNP	438	35
Watauga	Watauga	FNP	354	58
		Other Projects		
Raccoon Mountain	4/	P	pondage	1,530
Smaller projects	-	-	1,387	423
Totals			9,687	4,808

1/ reservoir purposes: F - flood control
N - navigation
P - hydropower

2/ all projects listed are owned by the Tennessee Valley Authority

3/ storage between normal full pool and winter flood control pool

4/ off-stream pumped-storage project

(2) The water resource development of the Tennessee River Basin is managed by the Tennessee Valley Authority (TVA). The TVA operates or controls 50 dams and reservoirs in the Tennessee River Basin, 33 of which have power facilities. Total reservoir storage is 13.8 million acre-feet, or about 30 percent of the average annual runoff. Table M-2 lists the major characteristics of the main river projects, the major tributary storage reservoirs, and the Raccoon Mountain pumped-storage project. Figure M-6 shows the locations of these projects.

b. System Operation.

(1) The primary operating objectives of TVA's river control plan are flood control, navigation, and power generation, although recreation, fish and wildlife, water quality, water supply, and vector control are also important. Unregulated streamflows are at a maximum during the winter months and at minimum levels during the summer and fall. The objective of the reservoir operating plan is to

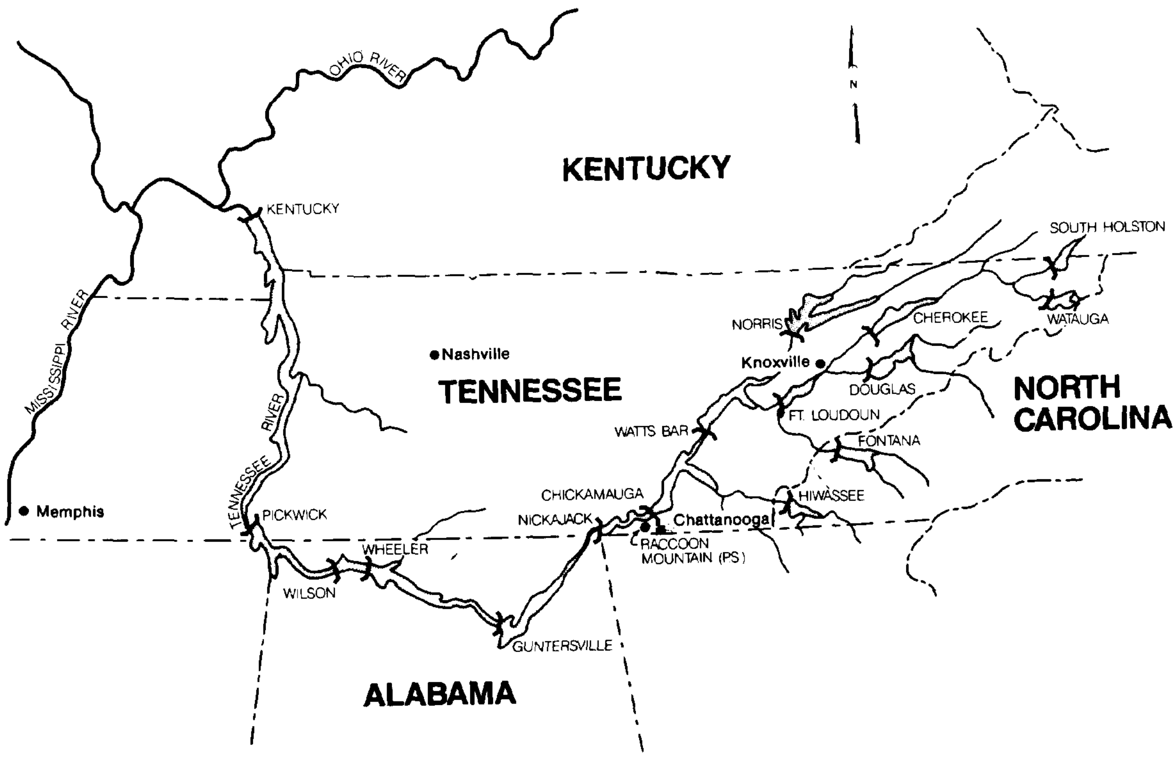

Figure M-6. Major projects of the Tennessee River system provide flood control, primarily in the winter months, and to augment streamflows in the summer and fall months for navigation, power generation, and other purposes.

(2) Power demand in the TVA service area is at its maximum in the winter months, but summer peak loads can be almost as high. TVA's hydro system was originally designed to carry the bulk of the system power demand, so most of the projects have relatively high average annual plant factors (40-70 percent). However, now that TVA has evolved into a thermal-based power system, the hydro plants are used primarily for carrying intermediate and peak loads. The 1530 MW Raccoon Mountain off-stream pumped-storage project was placed in service in 1979 to help carry peak loads.

(3) TVA's projects with seasonal regulating capability fall into two categories: (a) the tributary (or headwater) storage projects, and (b) the main river projects. Although the seasonal regulation pattern is basically the same in both cases, the details of the operations differ somewhat because of the differences in reservoir configuration, degree of control provided, and functions served.

c. Regulation of Tributary Storage Projects.

(1) The tributary storage projects are normally at or near maximum pool elevation about the first of June. A small amount of flood detention space is reserved through the summer months in order to control runoff from intense local storms. Storage draft begins in early summer and accelerates during the dry fall months to provide additional flows downstream for navigation, power generation, and low flow augmentation.

(2) The overall objective of the drawdown schedule is to have the storage drafted by the first of January in order to meet winter flood control requirements, but power generation requirements usually control the rate of draft. A basic power rule curve has been developed for each period in order to insure that firm power requirements are met (see Figure M-7). However, in most years reservoir and streamflow conditions are such that considerable flexibility exists as to how the storage would be drafted.

(3) Although the TVA has a substantial amount of hydropower capacity, it is now a thermal-based power system, so it uses its hydro generation to minimize system fuel costs. A set of intermediate guide curves is developed to govern storage draft (Chapter 5, Figure 5-49), and these curves are based on the expected value of hydroelectric generation over the course of the drawdown period. The decision to draft storage at any point in time is based on the amount

of reservoir storage available in the system and the cost of the most expensive (or marginal) thermal plant generation that would have to be operated in the absence of storage draft. If on any day the marginal cost of thermal generation exceeds the guide curve value corresponding to the reservoir storage available on that day, storage would be drafted and marginal thermal generation would be reduced or shut down. If the marginal cost of thermal generation is less than the guide curve value, storage drafts would be limited or water would be stored.

(4) The sequence of draft from the various tributary storage projects is based generally on optimizing system power generation and balancing relative storage among the projects. This objective is tempered by minimum discharge requirements for non-power purposes and the desirability of maintaining reservoirs as high as practicable during the summer months in the interest of reservoir recreation (within constraints imposed by the three primary operating objectives). The reservoir system configuration is a combination of series and parallel projects, with run-of-river and pondage projects interspersed among and downstream from the storage projects, so a system sequential streamflow routing model has been used to develop the system regulation plan.

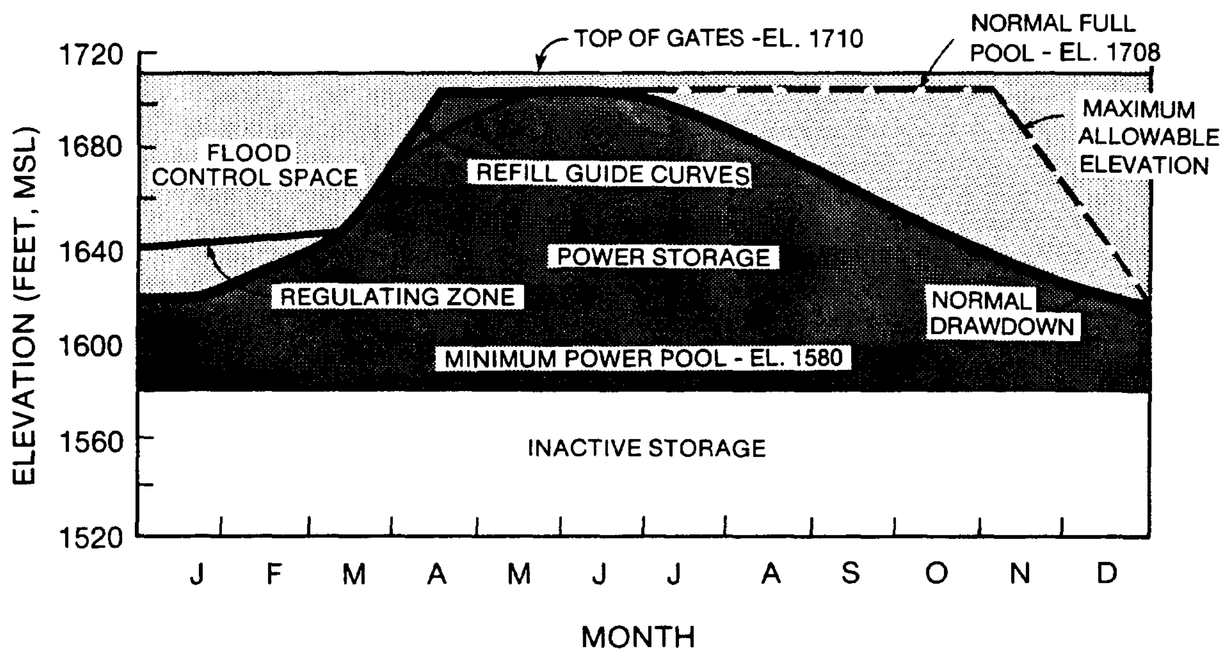

Figure M-7. Rule curve for Fontana Reservoir, a typical tributary storage project in the Tennessee River system

(5) The major flood control season includes the months of January, February, and March. Since there is no snowpack, these floods result from rainfall runoff. A specified amount of flood control storage space must be provided at each reservoir on March 15 to regulate floods at Chattanooga, a critical downstream location. The rule curve requires that additional storage space be available prior to March 15 in order to insure that earlier floods can be controlled without jeopardizing the March 15 requirement.

(6) The refill curve is based on balancing the diminishing flood control requirement with a reasonable probability of refilling the conservation storage. Operating procedures permit most reservoirs to be filled to the normal full pool level after the flood season. However, in some years, they do not refill completely.

d. Regulation of Main River Projects.

(1) The "main river projects" are the nine moderately low head (40 to 90 feet) projects that develop the hydro potential of the main stem of the Tennessee River from Knoxville to its confluence with the Ohio River, a distance of 625 miles. All of these projects have navigation locks, permitting barge traffic to be maintained through this reach. Wilson and Nickajack are run-of-river projects with pondage, but the remaining eight projects provide seasonal storage for flood control.

(2) Compared to the tributary storage projects, the main river projects have a relatively small amount of storage capacity in terms of inches of runoff (1.8 inches compared to 6.4 inches for the tributary reservoirs). However, these projects are useful in accelerating pre-flood flows downstream and in reducing the crest of the flood. Like the tributary projects, the main river reservoirs are required to be at their minimum elevations by 1 January (see Figure M-8). However, the total flood control space is reserved through the end of March, except when regulating floods. The winter flood control pool elevation is high enough to maintain adequate depth for navigation.

(3) Because of the relatively high ratio of runoff to storage space, these reservoirs are usually full by mid-April. Once the conservation storage is filled, the reservoirs are allowed to rise briefly into the summer flood control zone in order to strand floating debris. Storage drafts are scheduled through the summer and fall months for power production and other purposes to insure that the reservoirs will be at their winter flood control pool elevations by January 1. Because these projects are downstream reservoirs with relatively high streamflows, they are typically drafted later than the tributary projects, so that higher heads (and the resulting

higher power production) can be maintained as late as possible (see Chapter 5, Section 5-14). During the summer season, the main river projects are also operated on a weekly fluctuation cycle in order to control lake-breeding mosquitoes.

e. Critical Period. The 1939-41 critical drought period is used to establish the hydro system's basic power rule curve (Chapter 5, Figure 5-49). Because the TVA power system is an interconnected hydrothermal power system, the requirements for hydro firm energy and dependable capacity vary as a function of power loads, thermal plant performance, and purchase power availability. Because there is normally enough steam, combustion turbine, and import power available to meet hydro energy shortfalls caused by droughts, it is not necessary to reserve a large portion of the power storage for meeting firm energy requirements. This allows considerable flexibility in the use of this storage. As a result, resource allocation for the hydro system is based on expected output from an 82-year hydrologic record rather than protecting against the single worst drought of record. The overall operating strategy for hydropower is to minimize

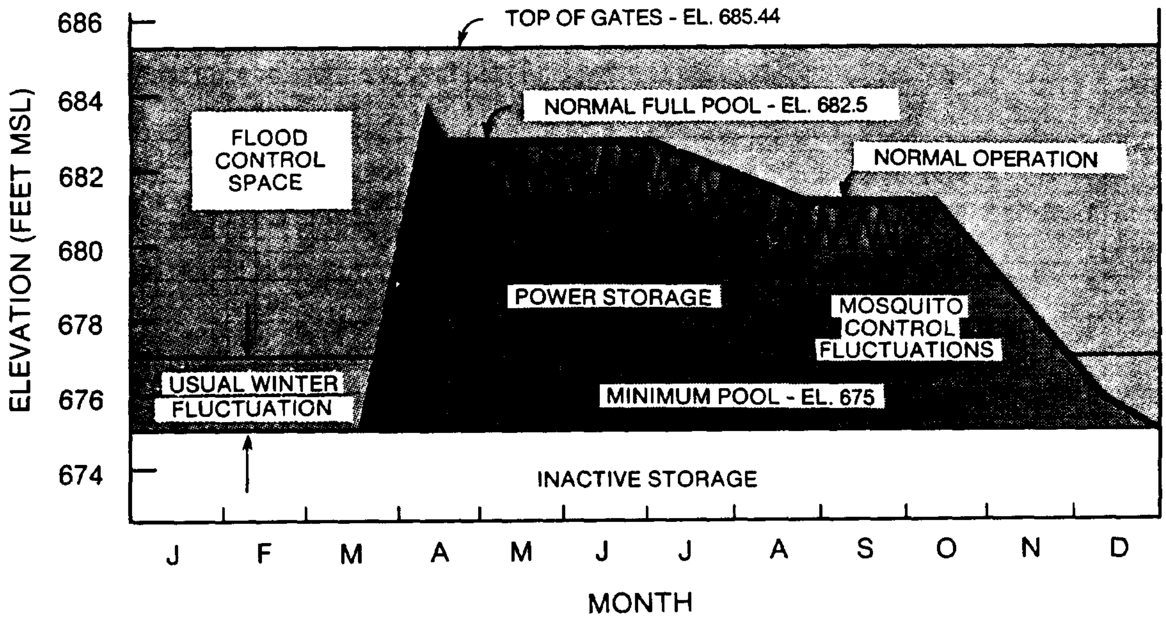

Figure M-8. Rule curve for Chickamauga Reservoir, a typical main river project in the Tennessee River system total system operating costs rather than maximizing firm energy output, so the classical critical period approach to reservoir regulation does not apply to the TVA system.

f. System Management. Operation of the Tennessee River reservoir system is managed by the Tennessee Valley Authority, Knoxville, TN 37902.

g. Summary. The TVA reservoir system is operated primarily to control winter floods and to provide conservation storage for power, navigation, and other river uses. Hydropower is used primarily to carry intermediate and peaking loads. The two operating features of the TVA system that are of special interest are: (a) that the relatively low-head main river reservoirs were designed to provide some seasonal storage capability, and (b) that storage drafts for power are based on the current value of the hydro energy for displacing thermal generation.

M-4. Arkansas River Basin System.

a. General.

(1) The Arkansas River drains 160,000 square miles of seven southwestern states and empties into the Mississippi River about 100 miles south of Memphis, Tennessee. Precipitation in the basin varies from 15 inches annually in its western reaches to more than 50 inches annually near the river's mouth. The majority of the precipitation occurs in May and June in the western portion of the basin and from March through May in the eastern section. Figure M-9 shows the seasonal runoff pattern for the Arkansas River at Van Buren, Arkansas, just downstream of the Oklahoma border.

(2) The Corps of Engineers and the Bureau of Reclamation have constructed 32 reservoirs in the basin, along with 17 locks and dams which permit shallow-draft navigation from the mouth of the Arkansas to Catoosa, near Tulsa, Oklahoma. This section describes the operation of the system of projects in the central part of the basin, which are regulated on a coordinated basis to meet the requirements of flood control, navigation, water supply, hydropower, recreation, water quality, and fish and wildlife. The major projects in this system are shown on Figure M-10, and their principal characteristics are listed on Table M-3. Ten of these projects have power facilities. The Grand River Dam Authority also operates three projects on one of the major tributaries, and two of these projects provide flood control storage, which is operated in coordination with the Federal projects.

b. Basic Reservoir Regulation.

(1) Reservoir space at most projects is divided into two zones: (a) an exclusive flood control zone on top, and (b) a conservation storage zone on the bottom (see Figure M-11). The seasons in which floods and droughts could occur overlap, so that it is not practical to provide a joint-use zone, such as that described in Section 5-12e of Chapter 5, in order to serve the needs of both flood control and conservation storage.

(2) Floods in the Arkansas River Basin are typically flashy, resulting from relatively short periods of intense rainfall. As originally designed, the flood control zone was intended to be evacuated as rapidly as possible following flood regulations. Conservation storage was to have been regulated to meet firm energy and water supply requirements. It was expected that regulation for flood control, power, and water supply would provide satisfactory conditions for navigation, except on the Verdigris River reach. A portion of the conservation storage at Oologah has been allocated to maintain navigation depth on the Verdigris during periods of drought.

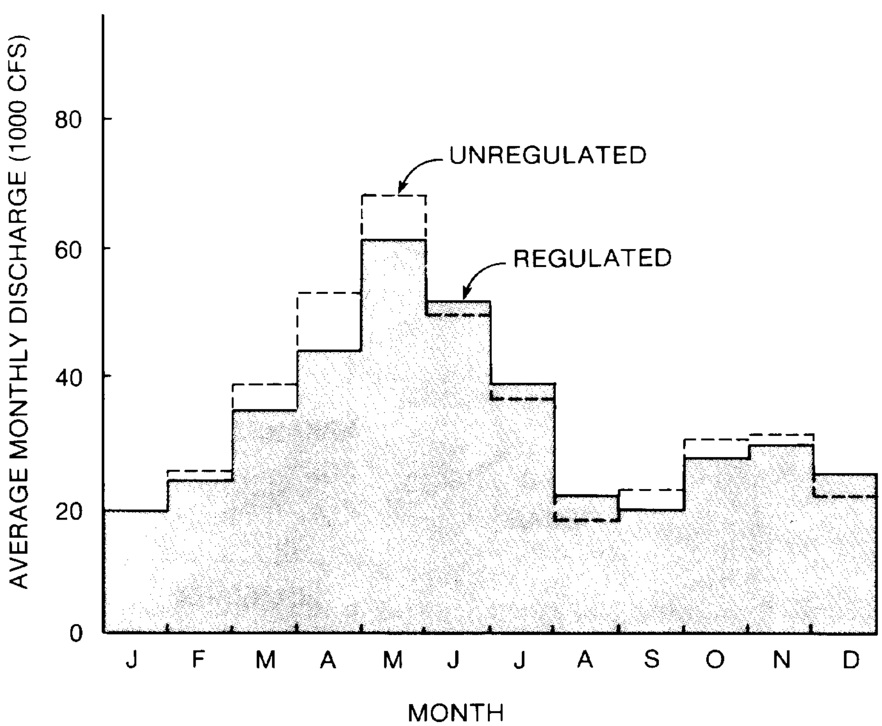

Figure M-9. Average monthly discharge of the Arkansas River at Van Buren, Arkansas, regulated and unregulated, 1940-1974

(3) The typical reservoir operating year begins in the late spring, with the reservoirs at their highest levels. Conservation storage drafts are normally made during the low flow summer months to meet power and water supply requirements, and these drafts can extend through the fall and winter months in many years. Conservation storage usually refills in the spring. Most of the major floods occur in the spring months, but high flows can be experienced at almost any time of the year.

(4) The power from the Corps' Arkansas River basin hydro projects is marketed by Southwestern Power Administration (SPA) as a system, together with projects in the adjacent White River basin. SPA serves a summer-peaking power system, with June, July, August, and September being the peak demand months. The original plan for regulating the conservation storage was based on maximizing firm energy production (while also maintaining water supply and minimum flow requirements).

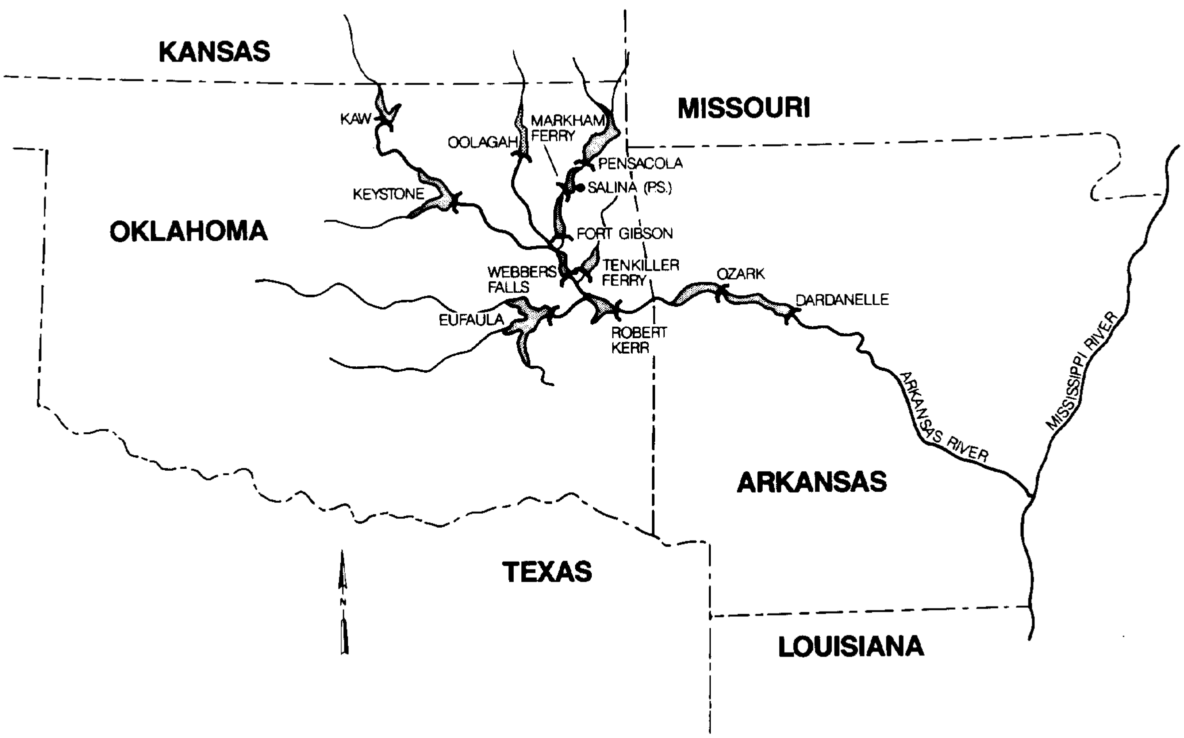

Figure M-10. Major hydroelectric projects in the Arkansas River Basin

TABLE M-3
Major Hydropower Projects in the Arkansas River Basin

Dam	River	Owner or Operator	Reservoir Functions	Conservation Storage (1000 AF)	Installed Capacity (MW)
Kaw	Arkansas	Corps	FRWSQ 1/	344	--3/
Keystone	Arkansas	Corps	FNPWS 4/	351	70
Oolagah	Verdigris	Corps	FNWS	544	--
Pensacola	Neosho	GRDA 2/	FP	586	86
Markham Ferry	Neosho	GRDA 2/	FP	pondage	108
Salina	off-stream	GRDA 2/	FP	p-storage	260
Fort Gibson	Neosho	Corps	FP	pondage	45
Webbers Falls	Arkansas	Corps	NP	pondage	60
Tenkiller Fy.	Illinois	Corps	FPS	371	37
Eufaula	Canadian	Corps	FNPRWS	1,481	90
Robt. S. Kerr	Arkansas	Corps	NPR	pondage	110
Ozark	Arkansas	Corps	NPRW	pondage	100
Dardanelle	Arkansas	Corps	NPRW	pondage	124
Totals				3,677	1,090

1/ reservoir purposes: F - flood control
I - irrigation
N - navigation
P - hydropower
R - recreation
W - fish and wildlife
S - water supply
Q - water quality

2/ Grand River Dam Authority

3/ in 1984 KAMO Electric Coop received a FERC license to install a powerplant at the Kaw project (final plant size not yet available)

4/ while many of the projects do not have recreation as an authorized project purpose, it is a major concern in developing operating plans for most of these projects.

(5) It was assumed that the full amount of reservoir storage allocated to power would be available for draft in order to meet firm power requirements. In the Southwestern states, hydropower is most valuable when used for peaking. Hence, most of the Arkansas and Red River basin hydro projects were designed to operate at firm plant factors in the low plant factor range. SPA's power sales contracts are essentially peaking capacity contracts, with each kilowatt of capacity being supported by a specified amount of firm energy. During periods of drought, the hydro system cannot fully meet these requirements, so thermal energy is obtained from local utilities under purchase and exchange agreements to make up the shortfall.

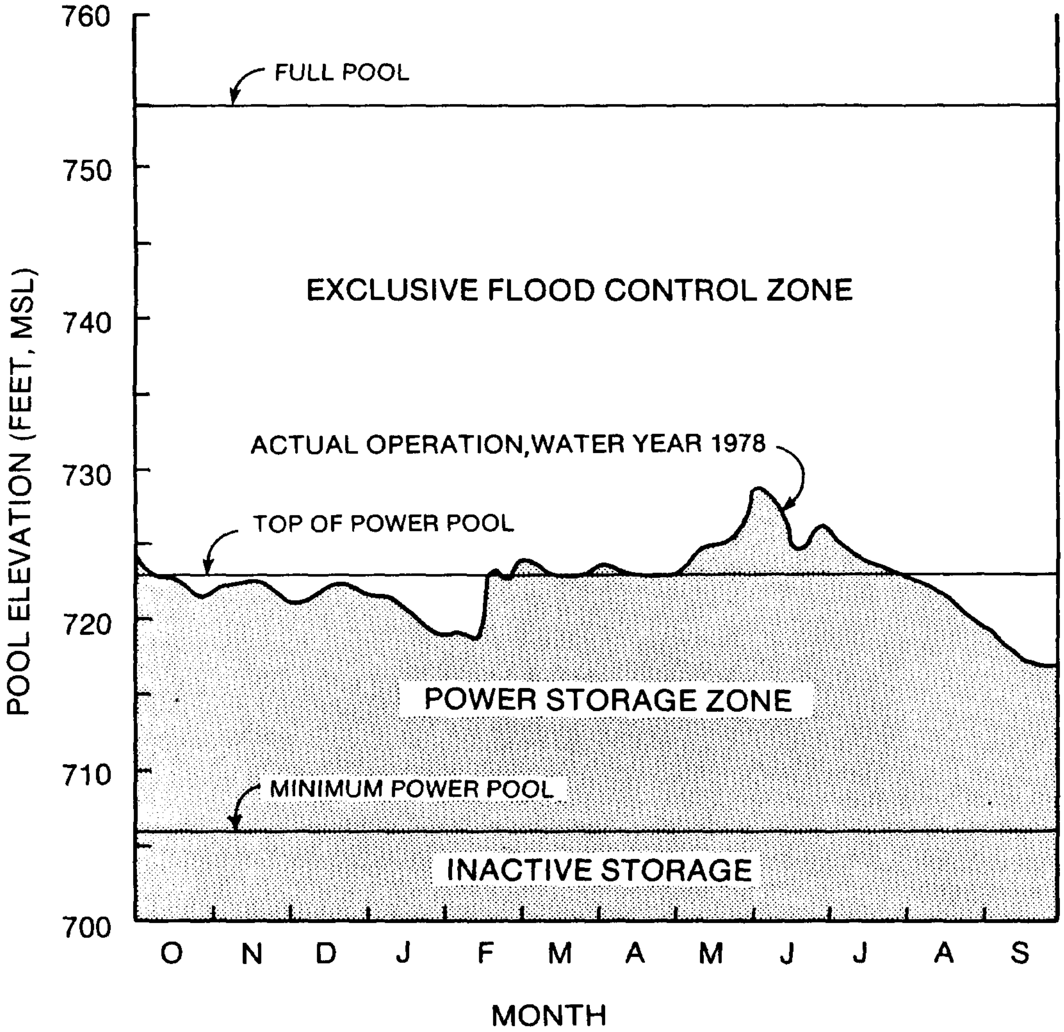

Figure M-11. Keystone Reservoir storage zones, showing actual operation in water year 1979

(6) When the reservoirs are operating in the flood control zone, the powerplants are generally operated at hydraulic capacity, and secondary energy is produced. Secondary energy could also be produced when operating in the conservation pool, depending on reservoir inflow, the time of year, and the power marketing situation.

(7) Operational experience has dictated two major changes to the operating plan: one when operating in the flood control zone and one when operating in the conservation storage zone. A description of these changes follows.

c. Modifications to Operation in Flood Control Zone.

(1) The rapid evacuation of the flood control space following flood events resulted in channel flows at or near bankfull capacity until evacuation was complete. At that point flows were reduced to those required to meet hydropower and water supply requirements. The sudden reduction in discharge would result in a corresponding sudden loss in river sediment transport capacity, leaving high shoals and blocked navigation channels in a number of reaches on the river. Furthermore, the discharges required to meet the rapid evacuation criteria exceeded the hydraulic capacities of the hydro plants, resulting in spilled energy. On the other hand, rapid evacuation of the flood control space left the storage space available as soon as possible for controlling subsequent flood events, thus maximizing flood control benefits. Rapid evacuation also brought the reservoirs down to the levels required for best reservoir recreation most rapidly.

(2) Because navigation is the dominant system function in terms of dollar benefits realized (more than 50 percent), a series of studies was made to develop a regulating plan which would improve navigation conditions during the post-flood evacuation period without significantly reducing flood protection. The result is a schedule of releases which is designed to provide a discharge level which is reduced gradually (or "tapered") as the flood control space is evacuated.

(3) The gage at Van Buren, Arkansas, near the Oklahoma-Arkansas border, is the control point upon which the regulation is based. When 40 percent or more of the basin flood control storage is filled, releases are scheduled at a rate such that flows at Van Buren do not exceed 150,000 cfs, which is the level at which structural flood damage occurs. When flood control storage is evacuated to the 40 percent level, releases are gradually reduced, so that by the time storage levels are in the 10-16 percent range, releases are at 105,000 cfs, the limit of agricultural flood damage. As the

remaining flood control space is evacuated, flows are maintained in the 20,000 to 40,000 cfs range, with 40,000 cfs being the level that corresponds to all power plants operating at hydraulic capacity.

d. Modifications to Operation in the Conservation Storage Zone.

(1) If the strategy of regulating the conservation storage to maximize firm energy production were to be followed rigorously, large storage drafts would be required on a regular basis. This would minimize SPA's purchases of supplemental thermal energy. On the other hand, the reservoirs would be frequently drafted to elevations that reduce (or threaten to reduce) generating capability below rated capacity. SPA has determined that maximizing dependable capacity is more valuable to their system than minimizing thermal energy purchases. Hence they prefer to purchase additional thermal energy in order to maintain the reservoir levels high enough to protect their dependable capacity.

(2) The power guide curves developed by Tulsa District illustrate this operation (see Chapter 5, Section 5-13d(3)). During periods of low flow, storage is drafted to support the capacity, but as the reservoir level drops, the hydro plant factor is gradually reduced. As the plant factor is reduced, increasing amounts of thermal energy must be purchased to meet SPA's energy requirements. During this type of operation, drafts must still be made for water supply and required downstream minimum flows, however.

e. Critical Period.

(1) The firm energy output of the Arkansas-White River hydro system is based on the 1952-56 critical period. The original studies assumed that the full amount of reservoir storage allocated to hydropower would be drafted during that period. At the present time, however, SPA regulates only the storage above rated head (see Chapter 5, Section 5-13c), so that rated capacity will be available at all times. The power storage below rated head is used to maintain head, rather than to increase firm energy output.

(2) While firm energy output is based on a multiple-year critical period, the reservoirs operate on an annual cycle. This is because of the relatively small amount of storage available compared to runoff. The multiple-year regulation serves primarily to identify the amount of thermal energy required to support the hydro generation in a critical year.

f. System Management. Operation of the majority of the Arkansas River reservoir system is managed by the Tulsa District, Corps of Engineers (PO Box 61, Tulsa, OK 74121). Little Rock

District (PO Box 867, Little Rock, AR 72203) is responsible for the portion of the basin located in Arkansas.

g. Summary.

(1) The Arkansas River reservoir system is operated primarily for flood control, hydropower, water supply, and navigation. The storage projects provide separate zones for flood control and conservation storage. Flood control storage is regulated to control flashy rainfall floods. The rate of evacuation of the flood control zone is based on a balance of three major considerations: (a) evacuating flood control space as soon as possible to provide space for controlling potential subsequent floods, (b) maintaining downstream rivers within bankfull capacities, and (c) minimizing sediment deposit by tapering the releases near the end of the evacuation period.

(2) Conservation storage is regulated primarily for power and water supply, and releases for these purposes are usually sufficient to meet navigation requirements. Only Oolagah has storage allocated for navigation. The conservation storage available in the system is equal to less than one-quarter of the basin's average annual runoff at Van Buren, so the degree of control is smaller than for some other basins. However, the storage does provide important benefits through the annual low flow period. Although the power storage was originally intended to be operated to maximize firm energy, present operation is oriented more toward maximizing dependable capacity. While recreation is not an authorized function at most of the storage projects, the lakes are heavily used for recreation, with the result that recreation does influence reservoir operation.

M-5. Missouri River Basin.

a. General.

(1) The Missouri River drains 520,000 square miles of ten midwestern states and about 10,000 square miles of Canada. Average annual precipitation over the basin ranges from 8 inches just east of the Rockies to about 40 inches in the southeastern portion of the basin and in parts of the Rockies. Normal seasonal maximum precipitation occurs throughout the basin during the period April-June. Snowfall in northern and central portions of the basin ranges from 20 inches in the lower basin to more than 100 inches in high elevation Rocky Mountain locations. High streamflows on the Missouri River are caused by plains snowmelt and rainfall during March and April and by mountain snowmelt and rainfall during the period May through July (see Figure M-12).

(2) In the 1930's and 1940's, a comprehensive plan for development of the water resources of the Missouri River Basin, the "Pick-Sloan Plan," was formulated by the Corps of Engineers and the Bureau of Reclamation. A number of the projects proposed in this plan have now been completed, including the six large reservoirs constructed by the Corps of Engineers on the Missouri River in Montana, North Dakota, and South Dakota (see Figure M-13). Sufficient usable storage space is available in these reservoirs to retain nearly two and one-half times the average annual flow of the Missouri River at Sioux City, Iowa. More than 90 percent of this storage is provided at Garrison (Lake Sakakawea, 18.9 MAF), Oahe (17.9 MAF), and Fort Peck (14.6 MAF), which are respectively the third, fourth, and fifth largest storage projects in the United States. Fort Randall (Lake Francis Case), like the large upstream reservoirs, also contains multiple-use carryover storage. Big Bend (Lake Sharpe) and Gavins Point (Lewis and Clark Lake) are pondage projects. Table M-4 summarizes the major operating characteristics of these projects.

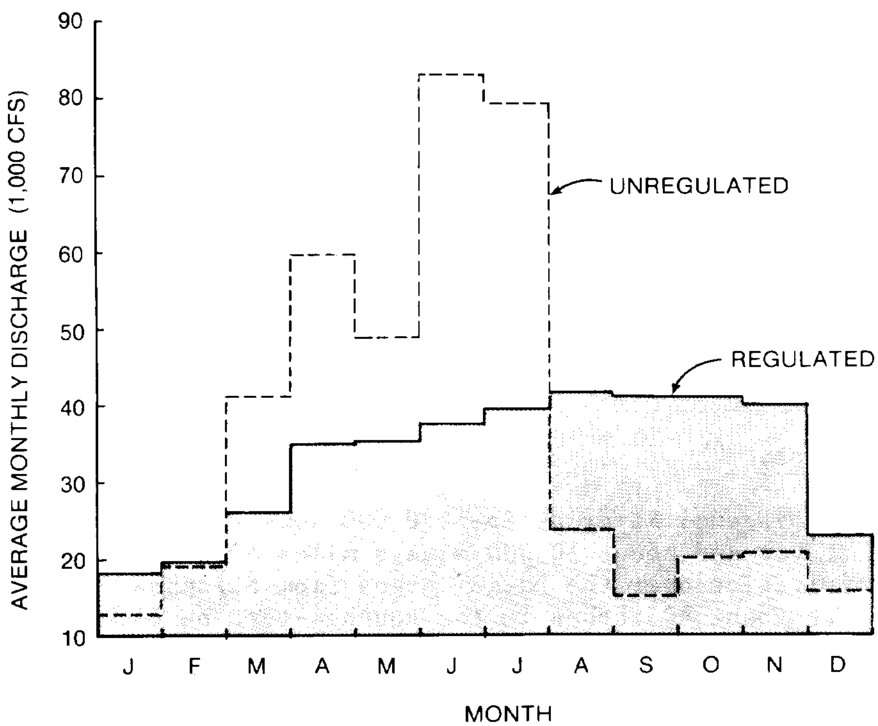

Figure M-12. Average monthly discharge of the Missouri River at Sioux City, Iowa, regulated and unregulated, 1967-1984

(3) This section describes the operation of the six mainstem projects, which are operated on a coordinated basis for flood control, navigation (on the mainstem Missouri River below Sioux City, Iowa), irrigation, hydroelectric power, municipal and industrial water supply, water quality control, recreation, and fish and wildlife.

b. Reservoir Regulation.

(1) Because of the reservoir system's large storage capacity and the basin's widely varying hydrologic conditions, the reservoirs must be regulated based on the projected long term future water supply as well as current conditions. The first system priority is to insure adequate flood protection. Second priority is to maintain enough seasonal storage to supply consumptive uses (irrigation and water supply) during anticipated future low flow periods. The consumptive use requirement totals about 20 percent of the total runoff at Sioux City and occurs primarily as pumping from the reservoirs or from the open reaches between the reservoirs. The remaining water is used to support navigation, generate hydropower, and to maintain suitable reservoir levels and outflows for recreation and fish and wildlife.

(2) Usable storage space at each of the four seasonal storage projects is divided into three zones (see Figure M-14). The uppermost zone is designated exclusive flood control storage space, which is reserved to control major floods. The next lower zone is designated as an annual flood control and multiple-use zone, which is regulated for seasonal flood control and to serve conservation requirements. Between the annual joint use zone and the dead storage zone is a carryover storage zone, which is used to support all project purposes during periods of extended drought.

(3) Releases for navigation are made to insure that adequate depths are maintained in the Missouri River between Sioux City and the confluence with the Mississippi River during the navigation season, which extends from about the first of April to the first of December. This typically requires releases from Gavins Point in the 28,000 to 35,000 cfs range. During the winter, ice bridges form on the river, precluding navigation. This ice could create local flood conditions if flows were maintained at the relatively high levels required for navigation. A discharge of 17,000 cfs is maintained from Gavins Point throughout the winter months for water quality and power production when water supply is adequate. Winter releases could be reduced to 6,000 cfs during extended drought periods.

(4) The firm power output of the projects, which is based on drought conditions (see Section M-5d), is marketed by the Western Area Power Administration to preference customers. This power is a mix of base load, intermediate, and peaking power. Energy is supplied on a two-step rate based on the customer's load factor. The standard rate applies so long as the customer's monthly load factor is 60 percent or less, and a higher rate is imposed if the load factor exceeds 60 percent. The higher rate is to cover thermal energy purchases that may be required to supplement the hydro at higher load factors. Energy in excess of preference customer requirements is marketed by WAPA to the area utilities at large. Excess energy is marketed primarily under two different rate schedules. Maintenance energy, which is typically available for a week or more, is sold at a fixed rate. Replacement energy, which has

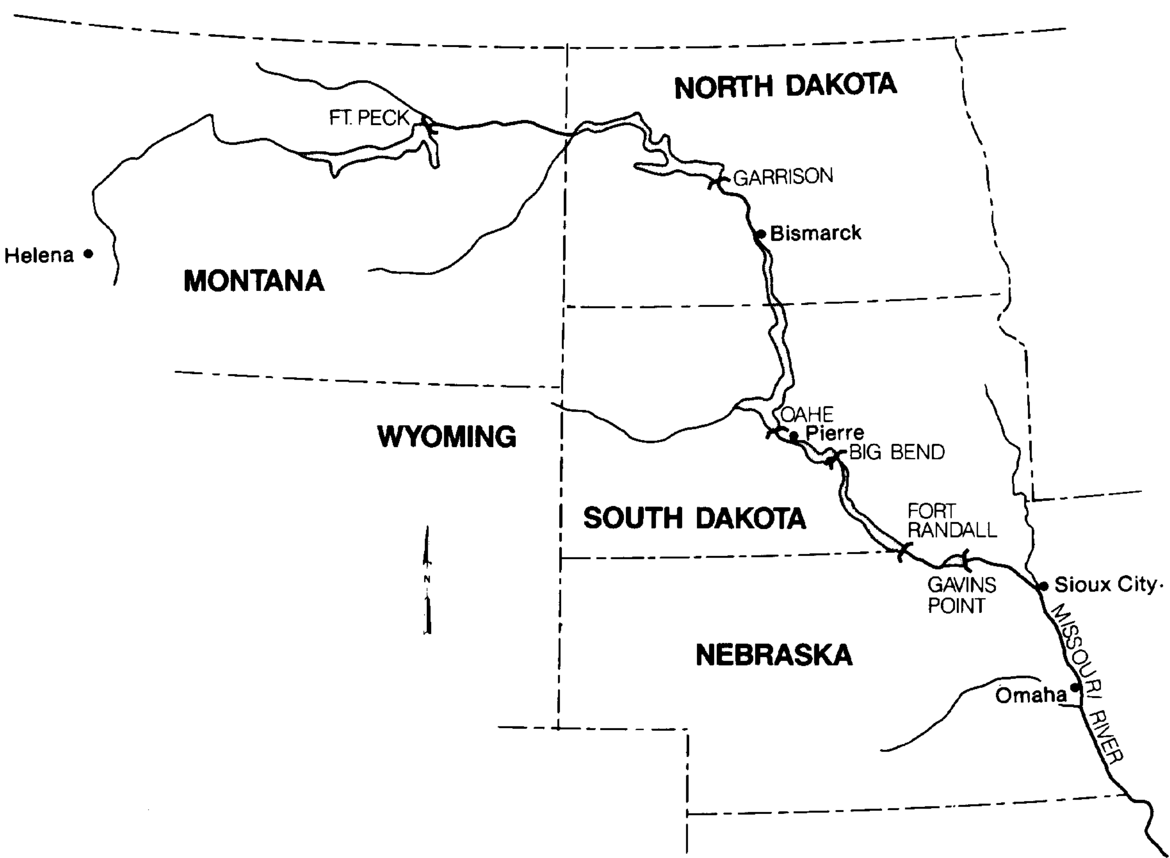

Figure M-13. Projects of the mainstem Missouri River reservoir system

TABLE M-4
Projects of the Mainstem Missouri River Reservoir System

Dam	River	Owner or Operator	Reservoir Functions	Usable Storage 2/ (1000 AF)	Installed Capacity (MW)
Fort Peck	Missouri	Corps	FINPRWS 1/	14,600	165
Garrison	Missouri	Corps	FINPRWS	18,900	400
Oahe	Missouri	Corps	FINPRWS	17,900	595
Big Bend	Missouri	Corps	FINPRWS	185	468
Fort Randall	Missouri	Corps	FINPRWS	4,000	320
Gavins Point	Missouri	Corps	FINPRWS	156	100
Totals				55,741	2,048

1/ reservoir purposes:
F - flood control
I - irrigation
N - navigation
P - hydropower
R - recreation
W - fish and wildlife
S - water supply

2/ storage at the major storage projects is allocated as follows (in million acre feet):

	Ft. Peck	Garrison	Oahe	Ft.Randall
Annual flood control and multiple-use	2.7	4.2	3.2	1.3
Carry-over multiple-use	10.9	13.2	13.6	1.7
Total conservation storage	13.6	17.4	16.8	3.0
Exclusive flood control	1.0	1.5	1.1	1.0
Total usable storage	14.6	18.9	17.9	4.0

shorter term availability, is marketed at a cost based on the value of the thermal plant fuel saved. The peak power demand occurs between mid-December and mid-February in the north portion of the marketing area due to home heating, and between mid-June and mid-August in the south due to air conditioning loads.

(5) The operating year begins with the reservoirs typically at their highest levels in July, following the spring snowmelt and early summer rains. The first step in the drawdown process is to evacuate the exclusive flood control zone if that space was required to control the spring runoff. Subsequent releases are made as required

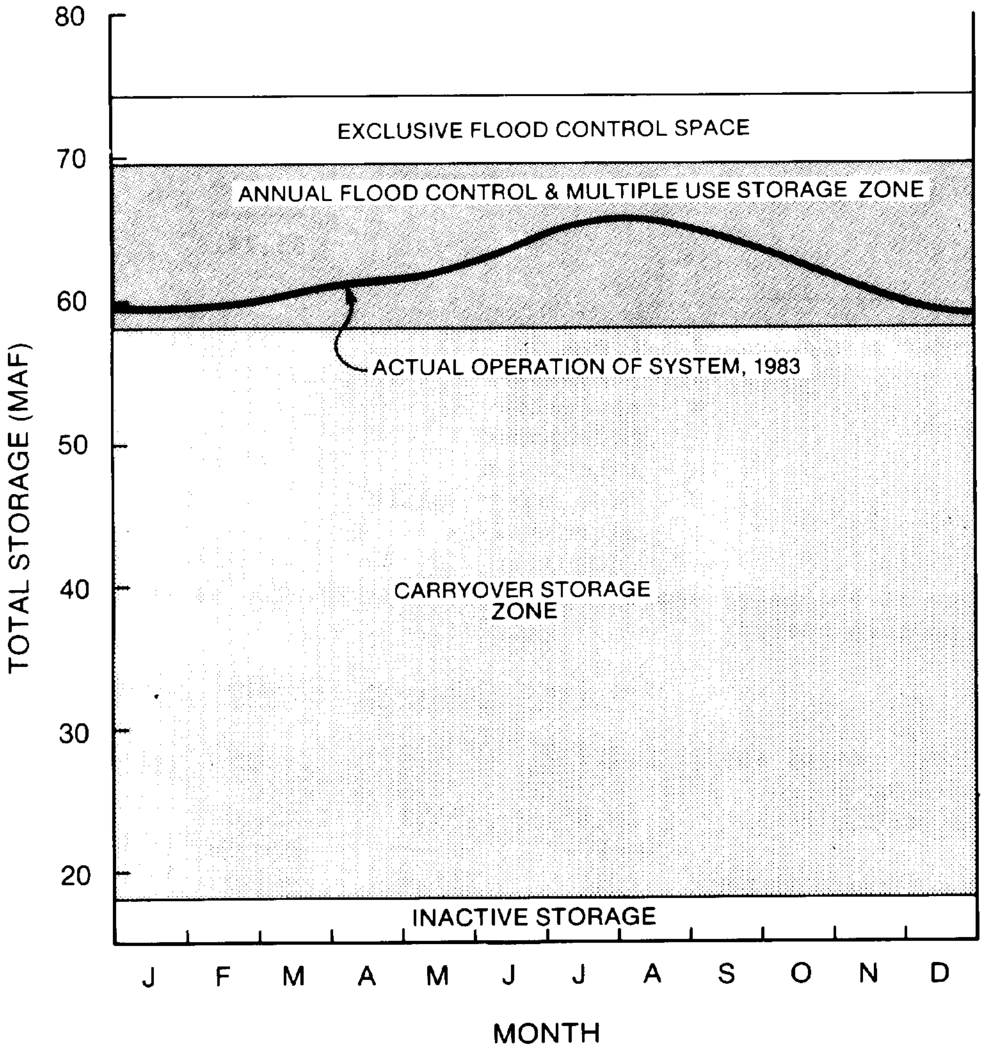

Figure M-14. Allocation of storage, mainstem Missouri River projects, showing actual operation in 1983 in order to maintain navigation flows on the mainstream Missouri through the remainder of the navigation season and to meet power requirements. In years of high runoff, it may be necessary to schedule releases in excess of that needed for navigation in order to evacuate storage to the desired level prior to the next flood season. The river freezes over and is closed to navigation in the winter months, and reservoir releases are at their lowest levels during these months. The river opens for navigation about the first of April, and releases are scheduled to meet these requirements. Further drafts may be scheduled in the early spring if the runoff forecast indicates that additional flood control storage is required. The refill period generally extends from early March until late July.

(6) In years of high runoff, the exclusive flood control zone may be used at some or all reservoirs. Because of the danger of floods resulting from summer rainstorms, this storage is evacuated as rapidly as possible within downstream channel capacity constraints. Releases in excess of powerplant capacities are scheduled when necessary. The flood control and multiple-purpose storage zone is regulated on an annual cycle. In normal or above-average runoff water years, this zone is filled during the refill season. On the average, approximately three-fourths of this zone is occupied at the time of maximum storage. Approximately one-half of this storage zone is needed to meet full service navigation requirements and average annual energy production through the drawdown season. The annual storage has only totally filled once in the first 18 years since the system reached normal operating levels. In most years it is almost completely drafted at the beginning of the upcoming flood season.

(7) In years when the annual storage does not reach the levels needed to maintain full service support to navigation, full support is continued only if a minor draft of the carryover storage is to be made. If a drought intensifies and more significant storage drafts would result, service to navigation is reduced by either shortening the eight month season or by reducing the river flows. Only once in the 18 years since the system first filled has less than full service to navigation been provided. In 1981, the season was shortened by three weeks.

(8) If two or more adverse water years occur in a row, the draft continues to be made in the carryover storage zone, and releases will be reduced to levels required to meet minimum navigation flow requirements. The reduced levels would require reduced barge loadings, and an increase in groundings would also result. In a severe drought, not only would flows be reduced, but the season length would be reduced to as short as four months. The

carryover storage is designed to meet these minimum requirements, as well as water quality and water supply needs, in a recurrence of the 12-year critical period 1930 through 1941.

(9) In years of above normal runoff, releases may be scheduled at rates in excess of navigation requirements in order to evacuate the system storage to the desired carryover levels. These higher than normal flows benefit navigation and hydropower by permitting increased barge loadings and increased generation.

c. Sequence of Drafting Storage.

(1) The six projects are situated in a series, and because of the differing seasonal requirements of the various storage uses, this presented an interesting problem in determining the optimum sequence in which conservation storage should be drafted. The way in which this problem was solved can best be illustrated by examining the two storage uses which have the greatest influence on the sequence of draft: navigation and hydropower. It must be remembered, however, that irrigation, municipal and industrial water supply, fish and wildlife, and water quality are also important reservoir functions, and they are sometimes the controlling factor in determining the discharge at individual projects.

(2) If hydropower were the only function to be considered, the upstream reservoirs would be drafted first (see Section 5-14). This strategy would result in maximum energy production, but it would also result in relatively low releases from the downstream project (Gavins Point) in the early part of the drawdown season (late summer-early fall) and relatively high discharges from that project in the winter and early spring. This release pattern is opposite to the requirements of navigation (see paragraph M-5b(3)), and according to the Act which authorized these projects, navigation has a higher priority than hydropower. The solution to this conflict was to develop a procedure for transferring storage among projects in such a way that power generation could be maximized to the extent possible within the downstream release constraints established by navigation (and within the constraints established by other project purposes).

(3) Storage releases from the system as a whole are generally greatest in the late summer and fall months, in order to meet navigation requirements. Energy requirements are high in the summer and low in the fall months, and could be accomodated during this period by a variety of draft sequences. However, power demand is also high during the winter months, when river navigation is not supported and downstream releases are reduced. The drafting sequence is therefore designed to transfer water among the reservoirs in such

a way as to maintain a high level of power output during both the summer and winter, while permitting high releases from Gavins Point in the summer and fall months and low releases in the winter months.

(4) During the summer and fall months, drafts required to meet the navigation requirements come primarily from the main downstream storage projects, Oahe and Fort Randall. Oahe is the first to be drafted, and it provides most of the releases in the late summer and early fall months. Fort Randall drawdown does not usually become significant until late September. However, once the Fort Randall draft begins, storage is drafted rapidly, so that maximum space will be available to capture winter storage releases from the upstream reservoirs. The Big Bend project, which is located between Oahe and Fort Randall, is a pondage project, and is operated generally in tandem with Oahe, with some daily and weekly regulation for peaking (because of operating limitations at the other projects, most of the peaking is done at Oahe and Big Bend). Gavins Point is also basically a pondage project, and it serves primarily as a reregulator, maintaining the desired flow conditions in the open river downstream.

(5) High summer releases from Oahe through Big Bend, Fort Randall, and Gavins Point mean high generation rates at those plants. To avoid generating more power than can be marketed advantageously under these circumstances, the usual practice during this time of year is to reduce releases and generation at Fort Peck and Garrison to levels required only to meet the needs of irrigation, fish and wildlife, and other river uses. This plan of operation results in a large share of the power being produced in the summer and fall months at the four downstream projects. This fits well with the high summer demand experienced in the southern part of the region, and it also leaves vacated storage space at the two major downstream storage projects (Oahe and Fort Randall).

(6) With the onset of the winter (non-navigation) season, conditions are reversed. Releases from Gavins Point drop to about one-third to one-half of summer levels, and the chain reaction proceeds upstream, curtailing discharges from Fort Randall, Big Bend, and Oahe. At this time, Fort Peck and Garrison releases are maintained at relatively high levels (within the limits of downstream ice cover), to partially compensate for the reduction in generation downstream. Because of the low winter discharge requirements at Gavins Point, a portion of this water is captured in the vacated storage space of Oahe and Fort Randall. In fact, Fort Randall normally refills much of its annual multiple-purpose storage zone during this period. Thus, winter power needs are met primarily by the manner in which water is passed from the upstream projects through Oahe and Big Bend to fill Fort Randall. In addition, this strategy results in a high percentage of the winter generation being

produced at the projects that are located in the northern part of the region, which experiences its highest power demand in the winter months.

(7) Figure M-15 shows the normal seasonal sequence of draft for the four major storage projects plus Gavins Point. Gavins Point is drafted late in the winter period in order to provide added seasonal flood control storage space during the spring months. Because it is the last project in the system, Gavins Point provides the final increment of control for flood regulation.

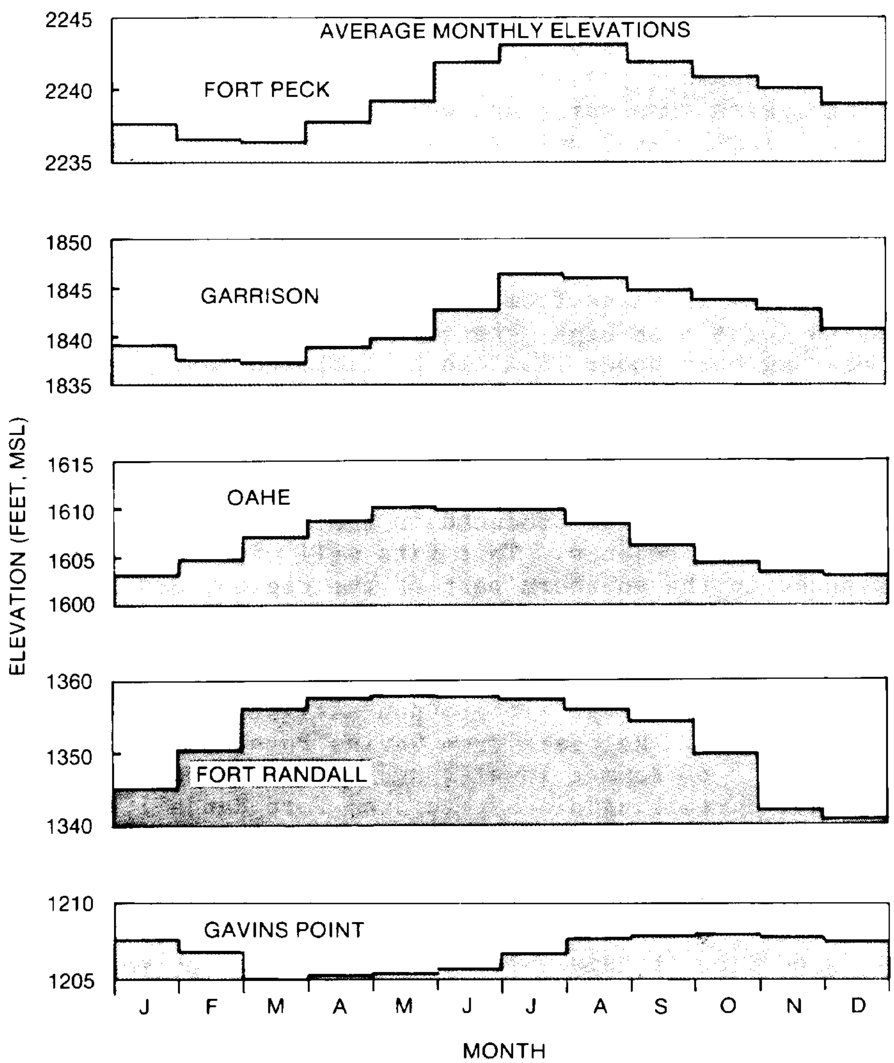

Figure M-15. Typical seasonal regulation patterns for the mainstem Missouri River storage projects

d. Critical Period. The firm yield of the Missouri River system is based on an eight-year drought that began in 1954. The critical year for establishing firm power is 1961. The storage is regulated to maximize firm energy production during this period while meeting minimum navigation flow requirements and consumptive use requirements for irrigation and municipal water supply.

e. System Management. The operation of the six mainstem Missouri River projects is managed by the Missouri River Division, Corps of Engineers, P.O. Box 103, Downtown Station, Omaha, NE 68101.

f. Summary.

(1) The storage regulation requirements of flood control, navigation and power generation are generally compatible with each other. The joint-use storage is drafted in the late summer, fall, and winter months to meet the requirements of navigation and power generation, leaving the space available for flood control in the spring and early summer months. The availability of exclusive flood control storage above and a considerable amount of carryover conservation storage below the annual joint use storage zone provides flexibility of operation while maintaining a high degree of reliablity in meeting operating objectives.

(2) The seasonal variation of navigation requirements, however, conflicts with the optimum operation of the reservoir system for power production. Maximum annual energy production would be achieved by drafting the upstream projects first. However, this would result in relatively low discharges from the downstream projects during the early part of the drawdown season, when high flows must be maintained for navigation, and high discharges near the end of the drawdown season (the winter months), when navigation is shut down and high flows can cause local flooding in the ice-choked river. A drawdown sequence was therefore developed which drafts the downstream reservoirs first. This provides high releases from Gavins Point for navigation in the summer and fall months while evacuating storage space in the downstream reservoirs. This space is refilled in the winter months while the upstream projects are being drafted for power production.

M-6. Colorado River Basin.

a. General.

(1) The Colorado River drains approximately 242,000 square miles located in seven western states. High annual flows in the Colorado River generally occur from April to July and are a result of

snowmelt in the Rocky Mountains (Figure M-16). The lower portion of the basin is quite arid, whith precipitation averaging only about five inches per year.

(2) Over 90 percent of the flow volume in the Colorado River Basin originates in the upper portion of the basin, above Glen Canyon Dam. Conversely, over two-thirds of the consumptive water use takes place at present in the lower portion of the basin. Therefore, the basin has become politically aligned into two sub-regions: (a) the Upper Basin states of Wyoming, Colorado, Utah, and New Mexico, whose present water requirements are relatively small, but who wish to reserve a "fair share" of the runoff for future use, and (b) the Lower Basin states of Arizona, Nevada, and California, who wish to protect their present water use and insure that additional water is available for future growth.

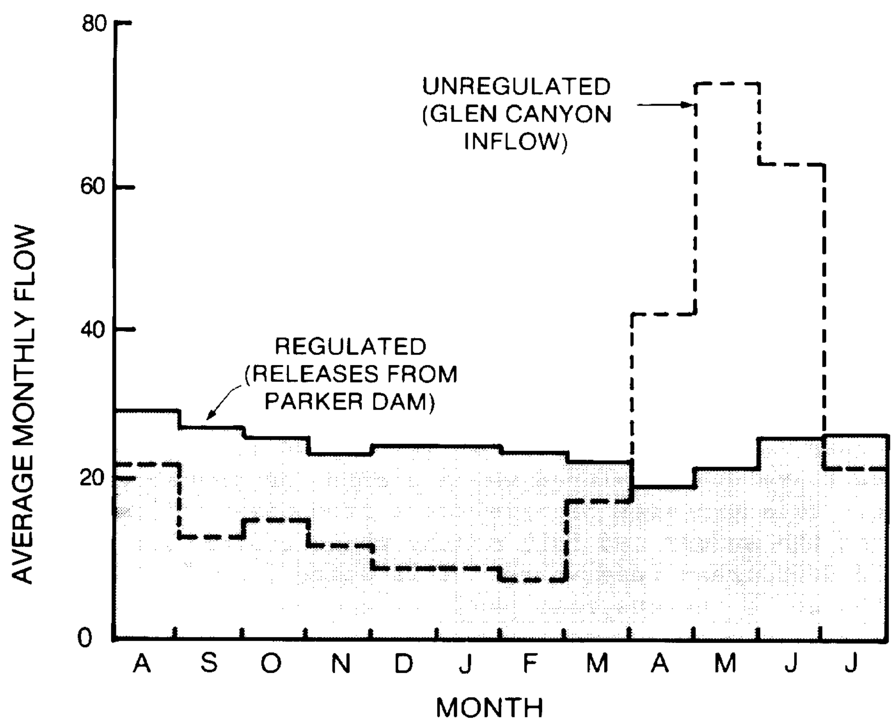

Figure M-16. Average monthly flow of the Colorado River, regulated (below Parker Dam) and unregulated (above Lake Powell), 1984-1985

(3) Although handicapped by lack of rainfall, the Lower Basin has many other desirable characteristics, and has attracted considerable agricultural and urban development. This development relies heavily on the Colorado River as its source of water, and this in turn has led to the development of an extensive system of dams, reservoirs, canals, pumping plants and other facilities, to insure that the water is delivered where and when it is needed.

(4) This system provides storage equal to about four times the average annual runoff of the Colorado River upstream of Lake Mead and a degree of control unmatched by any other large river basin in this country. This discussion concentrates on those system elements that have power facilities. This includes (a) the key storage projects in the system: Glen Canyon (Lake Powell) and Hoover (Lake Mead); (b) the primary reregulating facilities below Hoover: Davis (Lake Mojave) and Parker (Lake Havasu); and (c) some of the more important headwater storage projects: Flaming Gorge, Blue Mesa, and Navajo. Lake Mead at 27.4 MAF and Lake Powell at 25.0 MAF are the two largest reservoirs in the United States. Table M-5 lists the characteristics of these projects, as well as Morrow Point and Crystal, which are power and reregulation projects located downstream from Blue Mesa. Figure M-17 shows the locations of these projects.

(5) The Colorado River Basin projects are operated primarily for flood control, water supply (municipal and industrial as well as irrigation), and hydropower. Recreation, water quality, and fish and wildlife have also become important operating considerations. Operation of these projects is governed by a complex set of laws, compacts, treaties, and Supreme Court decisions, which are collectively referred to as the "Law of the River." Some of the major elements in the Law of the River are the interstate Colorado River Compact of 1922, the Boulder Canyon Project Act of 1928, the Mexican Treaty of 1944, the Colorado River Storage Project Act of 1956, and the Colorado River Basin Project Act of 1968.

(6) Major diversions in the Lower Basin begin at Lake Mead, where the Southern Nevada Project diverts water for the Las Vegas metropolitan area. Downstream at Lake Havasu, water is pumped by the Metropolitan Water District to urban Southern California via the Colorado River Aqueduct. The Central Arizona Project (CAP) is also beginning to pump from Lake Havasu, and when completed in 1992, the project will supply Colorado River water to the greater Phoenix and Tucson areas. Downstream from Parker Dam is the Headgate Rock Dam, which diverts water to irrigate agricultural lands of the Colorado River Indian Reservation near Parker, Arizona. The Palo Verde diversion dam supplies water to the Palo Verde Irrigation District near Blythe, California. Imperial Dam is the last diversion dam in the United States. It diverts Colorado River water into two canals:

TABLE M-5
Major Projects of the Colorado River
Multiple-Purpose Reservoir System

Dam	River	Owner or Operator	Reservoir Functions	Active Storage (1000 AF)	Installed Capacity (MW)
Blue Mesa	Gunnison	USBR	FISP 1/ 4/	749	60
Morrow Point	Gunnison	USBR	P	pondage	120
Crystal	Gunnison	USBR	P	pondage	28
Flaming Gorge	Green	USBR	FISPR 4/	3,516	108
Navajo	San Juan	USBR	FIS 4/	1,036	--
Glen Canyon	Colorado	USBR	FISPR 4/	25,000	2/1,206
Hoover	Colorado	USBR	FIPSRW	27,377	3/1,340
Davis	Colorado	USBR	IPSRW	1,810	240
Parker	Colorado	USBR	FIPSRW	180	120
Totals				59,668	3,222

1/ reservoir purposes: F - flood control
I - irrigation
P - hydropower
R - recreation
W - fish and wildlife
S - water supply (municipal and industrial)

2/ of which 20,876 KAF is usable for power generation

3/ of which 17,400 KAF is usable for power generation

4/ Flood control benefits at these projects are incidental to operation for other project purposes

(a) the Gila Gravity Canal, which supplies water to the Yuma Mesa and Wellton-Mohawk Projects in Arizona, and (b) the All-American Canal, which supplies water to the Coachella and Imperial valleys in California.

b. System Operation-General.

(1) The Colorado River reservoir system is an example of a system with sufficient storage to provide nearly complete control of the lower portion of the river. This control extends beyond seasonal control, in that large amounts of carry-over storage permit meeting

water requirements through multiple-year drought periods. This degree of control will become increasingly important as the Central Arizona Project is completed and the total consumptive use in the basin begins to approach the average annual inflow to the system.

(2) The history of the operation of the Colorado River reservoir system has been one of continual change. The physical characteristics of the reservoir system have changed over the years

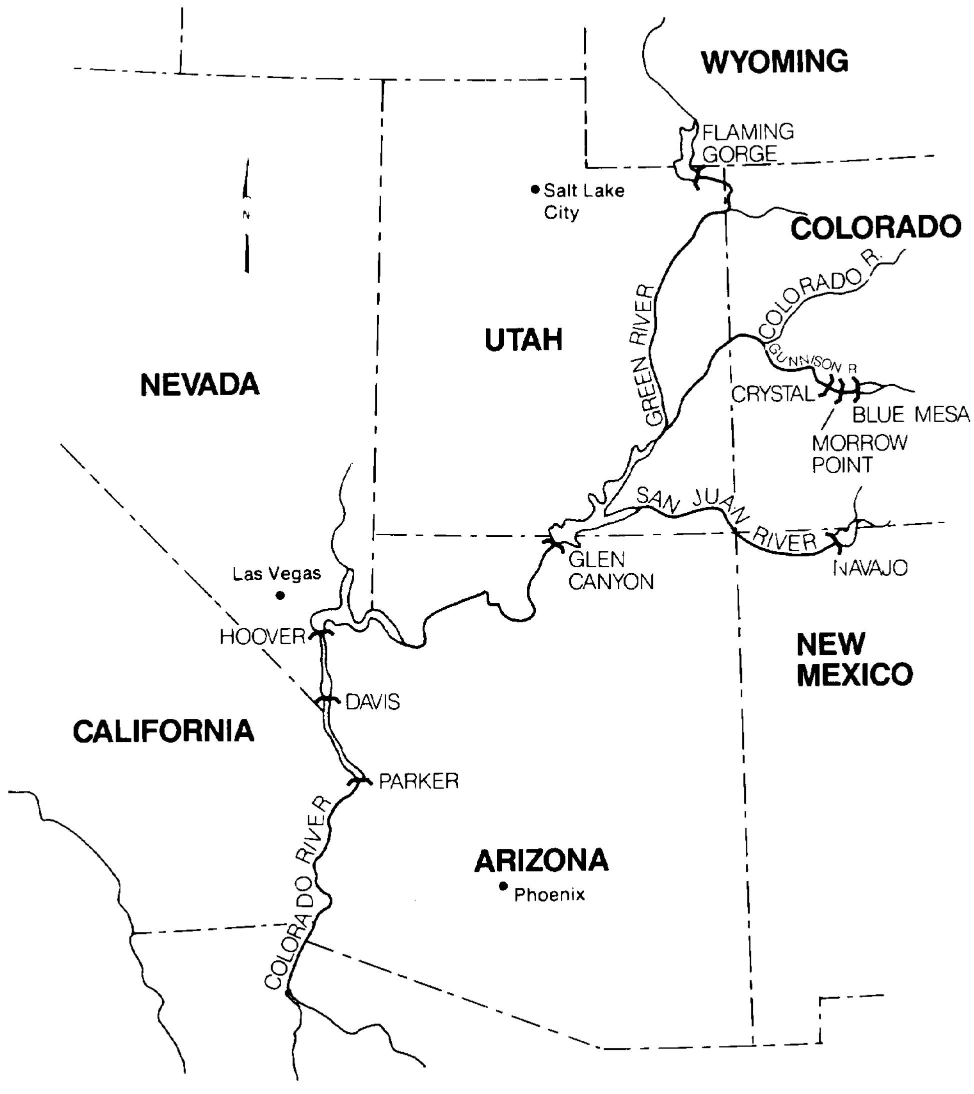

Figure M-17. Major projects in the Colorado River system as projects have been completed and the reservoirs have filled. The demands imposed on this system have been increasing as the region has developed. Perhaps most importantly, the Law of the River is continuing to evolve, in response to conflicting demands on the system and conditions that were not entirely anticipated when the initial laws and agreements were written. For these reasons, it is not yet possible to write a definitive description of the operation of this system. The following paragraphs therefore constitute only a general description of how the system is operated at the present time.

(3) Through the language of the Boulder Canyon Act of 1928, which authorized Hoover Dam, Congress established the operational priorities of the Colorado River reservoir system, specifically:

- controlling floods
- improving navigation and regulating the flow of the Colorado River
- providing for the storage and delivery of the stored waters for reclamation of public lands and other beneficial purposes
- generation of electrical energy

Superimposed on this is the Treaty requirement of providing 1.5 MAF annually to Mexico at the border. As a practical matter, water supply for irrigation and municipal and industrial (M&I) use is the dominant river use, and the primary purpose of system regulation strategy is to meet current water supply requirements and to insure that adequate reservoir storage is maintained to protect future requirements. Flood control does have a higher priority, particularly at Hoover, but this function will control operation only when the system is near full (see Sections M-6d(8) and (9)). Hydropower generation is maximized to the extent possible within the constraints imposed by the higher priority uses.

(4) Because of the flexibility required of the Colorado River system, the reservoir storage has not been formally allocated into zones. Therefore, it is not possible to prepare a detailed system rule curve. Figure M-18 shows only the approximate seasonal allocation of reservoir storage in the system.

(5) The top zone is 1.5 MAF of exclusive flood control space, which is provided at Lake Mead for the control of summer rainfall floods. Below this is a joint use zone, which is regulated for control of snowmelt floods and for seasonal conservation storage for water supply and power generation. The remaining storage, which constitutes the bulk of the usable storage capacity, is carry-over conservation storage, which is used to support firm water supply and power generation requirements in periods of extended drought.

c. Flood Control Operation

(1) Flood control requirements are designed primarily to protect the heavily developed reaches of the Colorado River below Davis and Parker Dams. The Hoover Reservoir (Lake Mead) is the key element in the flood control operation, with the other reservoirs contributing storage space to the extent possible, consistent with other project requirements. The headwater reservoirs also provide some local flood protection. The primary objective of the flood

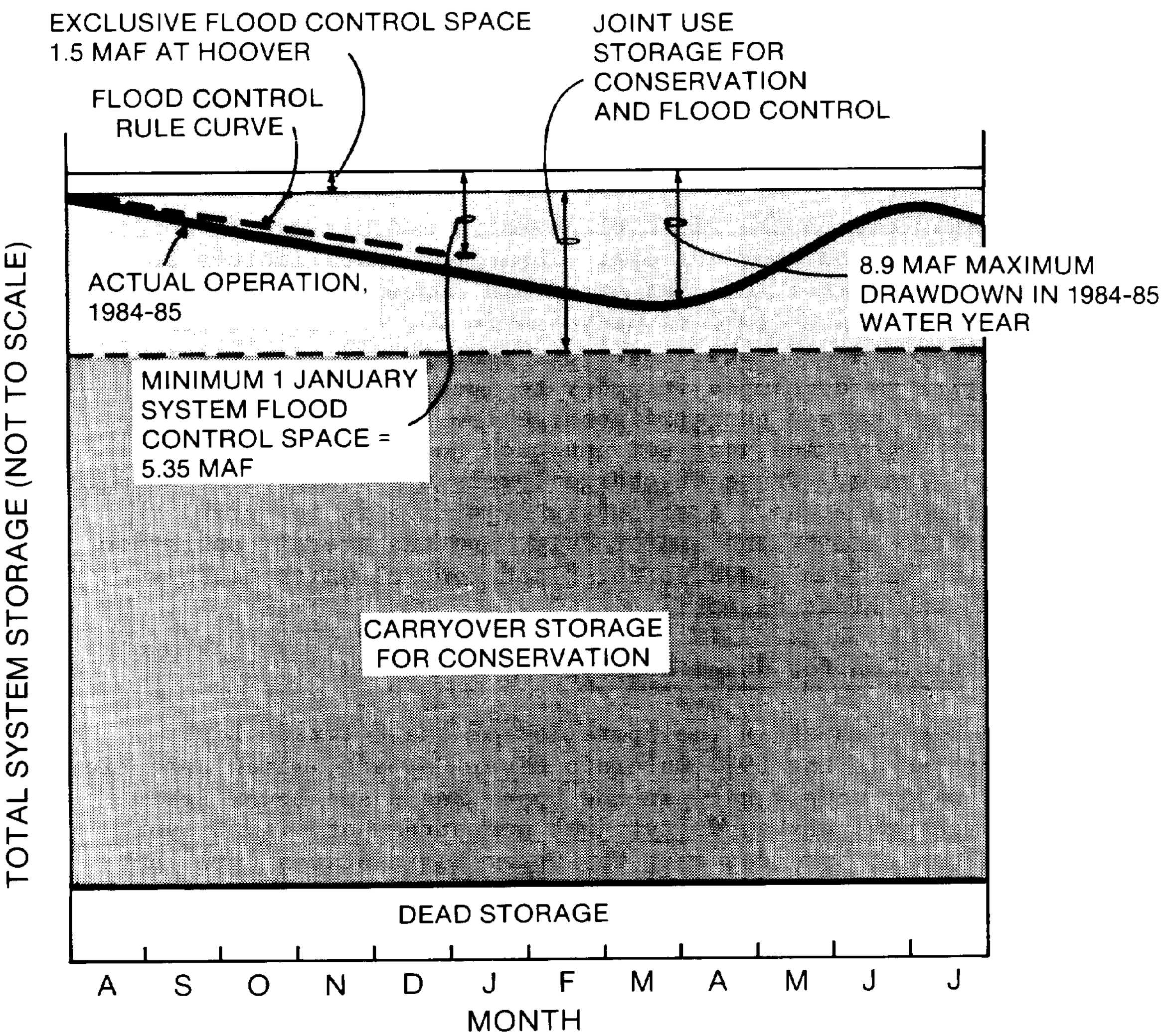

Figure M-18. Seasonal allocation of storage in the Colorado River system control operation is control of the spring snowmelt runoff, although a minimum of 1.5 MAF of flood control space is provided at Lake Mead to control summertime rainfall floods. As mentioned earlier, flood control influences reservoir operation only when the system is near full. When adverse water conditions have drawn the system into the carry-over storage zone or when a low spring runoff is anticipated, refill of conservation storage rather than flood control governs the reservoir operation.

(2) For those years when flood control is required, the following procedures are applied. At the end of the refill season (31 July), a minimum of 1.5 MAF of space is provided at Lake Mead for rainfall flood control. Over the next five months, drafts are scheduled to insure that a minimum of 5.35 MAF of flood control space is available in the reservoir system on 1 January. This is accomplished in part with drafts to meet water supply and irrigation requirements, but additional releases may be required in years of high runoff.

(3) Beginning on the first of January, monthly runoff forecasts are prepared based on snow surveys. These forecasts include an adjustment for possible forecast error and represent a runoff volume that has an exceedance level of only one in 20. Using the runoff forecast volume and available reservoir storage space, a reservoir regulation plan is developed in order to insure that flows below Davis Dam do not exceed target discharge levels and that the Lake Mead reservoir elevation does not encroach on the summer rainfall flood control space. These discharge levels are designed to minimize downstream flood damages. A secondary objective is to refill conservation storage by the end of July, and the overall operation results in the maximum drawdown for flood control which usually occurs about the first of April.

d. Regulation for Water Supply.

(1) A key element in the operation of the Colorado River reservoir system is the 1922 Colorado River Compact, which apportions the basin's water supply between the Upper Basin and Lower Basin states (as measured at Lee Ferry, just downstream of Glen Canyon Dam). The compact provides that the Upper Basin states "will not cause the flow at Lee Ferry to be depleted below an aggregate of 75 MAF for any period of 10 consecutive years." This is sometimes expressed as an average annual allocation of 7.5 MAF to the Lower Basin states.

(2) Development of the Lower Basin has progressed to the point where nearly the full apportionment of water is already required to meet irrigation and M&I water supply needs. Unfortunately, the

basin's natural runoff varies considerably, both within the year (Figure M-16), and from year to year, ranging from less than 6 MAF to nearly 25 MAF, and periods of four or five consecutive years of below average runoff are not unusual. Hence the objective of the Colorado River reservoir system is to convert this fluctuating runoff into a stable water supply.

(3) Glen Canyon (Lake Powell) is the keystone of this operation, with nearly 21 MAF of active storage (above the power intake), most of which can be classified as drought year carry-over storage. The headwater reservoirs (Flaming Gorge, Blue Mesa, and Navajo) provide additional regulating capability. The overall objective of the reservoir operation is to meet the Upper Basin's obligation to the Lower Basin at the Compact point (Lee Ferry) without impairment of Upper Basin consumptive uses during a period of extended drought. A secondary objective is to insure that additional water that is not required to meet the consumptive use requirements of the Upper Basin (but which could be used in the Lower Basin), will not be withheld from the Lower Basin.

(4) These objectives are defined in the Colorado River Basin Act of 1968, and Section 602(a) of that Act directs that criteria be established for determining the amount of carry-over storage that must be maintained in Glen Canyon and the headwater reservoirs to insure that these objectives will be met. The Secretary of the Interior has proposed criteria for computing the annual storage requirement (usually referred to as "602(a) storage"), but complete agreement has not yet been reached between the Upper Basin and Lower Basin states on this methodology. Hence, the operation described in the next paragraphs should be considered as one example of how the 602(a) storage requirement could be computed, but it should not be construed as being the official procedure.

(5) The first step is to select a critical streamflow period. Such a period might be the driest on record, or perhaps one having a 90 or 95 percent chance of exceedance. Take, as an example, the driest 12-year inflow above Lake Powell. The total water requirements on the system would be the sum of the estimated depletions from the Upper Basin for the next 12 years and an annual release to the Lower Basin from Glen Canyon of 8.23 MAF over the same period (8.23 MAF is the sum of 7.5 MAF, from paragraph (1), above, and approximately half of the 1.5 MAF Mexican treaty requirement). The difference between the total requirements and the 12-year inflow volume is the storage needed at Lake Powell and the headwater reservoirs to satisfy that year's 602(a) storage requirement.

(6) The 602(a) storage requirement is computed every year and compared with the amount of storage actually available in the reservoir at the end of the runoff season. If the available storage is less than 602(a) storage requirements, releases from Glen Canyon over the next year will be limited to 8.23 MAF. If the available storage is greater than the 602(a) requirement, surplus water is available, and Glen Canyon will release sufficient water to equalize storage at Lake Powell and Lake Mead by 30 September.

(7) Hoover Reservoir (Lake Mead) has about 27 MAF of storage capacity to the top of the exclusive flood control pool. In addition to providing flood control, this storage is used to store water released from Glen Canyon that is not needed to satisfy immediate downstream water requirements. The Glen Canyon seasonal release pattern is designed primarily to meet power requirements and avoid spills. These demands differ from the seasonal use pattern of the irrigation and M&I customers below Hoover, so the Hoover storage is used to provide the necessary seasonal reshaping. Finally, substantial evaporation and transpiration losses occur in the Hoover, Davis and Parker reservoirs, as well as from the open river reaches. These losses must be made up with drafts from Lake Mead.

(8) The degree of interplay between flood control and water supply (consumptive use) can best be described by examining the history of reservoir operation at Hoover. Until Glen Canyon Dam was completed in 1963, flood control releases dominated the annual operating plan at Hoover. Once filling of the Glen Canyon Reservoir (Lake Powell) began, ample flood control space was available in the partially-filled Lake Powell, so Hoover released only sufficient water to meet water supply requirements. Lake Powell filled in 1980, and the reservoir system was once again full. Since that date, flood control has again become the controlling function at Hoover, and releases have been made in excess of water supply requirements in order to insure that sufficient storage is available to maintain freshet season releases at levels which would minimize damage downstream.

(9) This mode of operation is expected to continue into the 1990's. By the mid-1990's, however, consumptive use requirements could begin to exceed the average inflow to the system. During periods of drought, heavy drafts will be required in order to meet water supply needs, and reservoirs will frequently be at levels below which flood control requirements control reservoir operation.

e. <u>Operation for Hydropower.</u>

(1) The basic annual operating plan for the reservoirs in the Colorado River system is defined by water supply requirements and,

where applicable, flood control requirements. However, within these constraints, some flexibility is given to power generation. The amount of flexibility varies from project to project.

(2) At Glen Canyon, the annual operating plan defines the amount of water to be released by month in the operating year. Within these constraints, the project is operated primarily for power production. For example, once the annual discharge requirements have been established, the day to day releases are defined primarily by power requirements. Power is marketed on a firm basis with firm energy defined as the project's average annual energy production. When Glen Canyon's discharge is insufficient to meet firm requirements, the shortfall is made up with thermal energy purchases. Daily operation is primarily to meet peak loads.

(3) At Hoover, the monthly discharges are defined primarily by water supply requirements, which differ considerably from the seasonal power demand pattern. Hence, some of the generation is usable only as thermal energy displacement. However, within each month, considerable flexibility exists in how the generation can be scheduled and the Hoover powerplant is normally operated for peaking.

(4) Parker and Davis Reservoirs have only limited storage capability, so the operation of Hoover must be coordinated with the operation of these projects. The main function of these projects is to regulate the Hoover discharges such that downstream and diversion water supply requirements are met. For example, both the Central Arizona Project and the Metropolitan Water District's Colorado River Aqueduct pump from the Parker reservoir, and there are a number of projects that draw from the Colorado River below Parker Dam. The power generation at Parker and Davis is scheduled within the limits imposed by these requirements.

f. Critical Period. As noted in paragraph M-6d(5), the annual 602(a) storage requirements for Glen Canyon and the headwater reservoirs are based on a critical drawdown period which is multi-year due to the large amount of storage compared to runoff in the system. However, because of the dynamic state of the Colorado River system and the fact that final agreement has not yet been reached on procedures for defining the 602(a) storage requirement, it is not possible at the present time to identify a single critical period that defines the system's firm yield.

g. System Management. The Colorado River Basin storage projects are operated by the Bureau of Reclamation, and Reclamation has primary responsibility for the system operating plan. The Upper Colorado Region (PO Box 11568, Salt Lake City, UT 84147) is responsible for Glen Canyon and the headwater projects, and the Lower

Colorado Region (PO Box 427, Boulder City, NV 89005) is responsible for Hoover, Davis, and Parker. Because the Colorado River Compact is one of the primary documents governing the operation of the system, the states also play a major role in the development of the operating plan. The Corps of Engineers is involved in the flood control aspects of the plan.

h. Summary. A high percentage of the Colorado River's runoff has been appropriated, primarily for irrigation and M&I water supply. Storage facilities having a usable capacity of about four times the average annual runoff have been constructed to (a) regulate the seasonal runoff to fit the seasonal demand pattern, and (b) to provide carryover storage to permit meeting water supply requirements during periods of extended drought. The reservoirs also provide flood protection for the highly developed reaches below Davis and Parker Dams. Flood control operation conflicts with the regulation for water supply in that it can reduce the probability of refill. Within the constraints of flood control operation, water supply requirements define the basic annual operating plan: i.e., how much water is to be stored in or drafted from the major storage projects during the operating year and what is to be the monthly release pattern from Hoover. The hydropower operation must fit within these constraints. The result is limited flexibility in matching generation to the seasonal demand pattern (except at Glen Canyon), but considerable flexibility in the daily scheduling of generation within the monthly release requirements. Because of the high degree of control of the river, the average annual generation of the system is marketed as firm power, with thermal purchases being made to cover for the occasional shortfall.

M-7. Central Valley Project, California.

a. General.

(1) California's Central Valley Project (CVP) is located in the Sacramento and San Joaquin River basins, entirely within the northern two-thirds of the State of California. Six of the 10 leading agricultural counties in the United States lie in the project area. Precipitation in this area is almost exclusively in the form of rainfall and ranges from 30 inches annually in the northern sections of the valley to 5 inches in the south. Three-quarters of this rainfall occurs in the period December-March, during the non-irrigation season. Since rainfall is sparse during the growing season, crops depend primarily on surface water and groundwater for irrigation. Figure M-19 shows the seasonal runoff pattern for the Sacramento River.

(2) The primary purpose of the Central Valley Project is to provide a reliable water supply for the rich agricultural lands of the semi-arid Sacramento and San Joaquin Valleys. Flood control and hydroelectric power generation are also important functions. A substantial amount of power generation is required to meet Project pumping requirements, and revenues from generation above these requirements serve to help repay the cost of reservoirs and other facilities. Reservoir recreation, navigation on the Sacramento River, municipal and industrial water supply, fish and wildlife, and control of salinity intrusion in the Sacramento-San Joaquin River delta also have an important influence on how the system is operated.

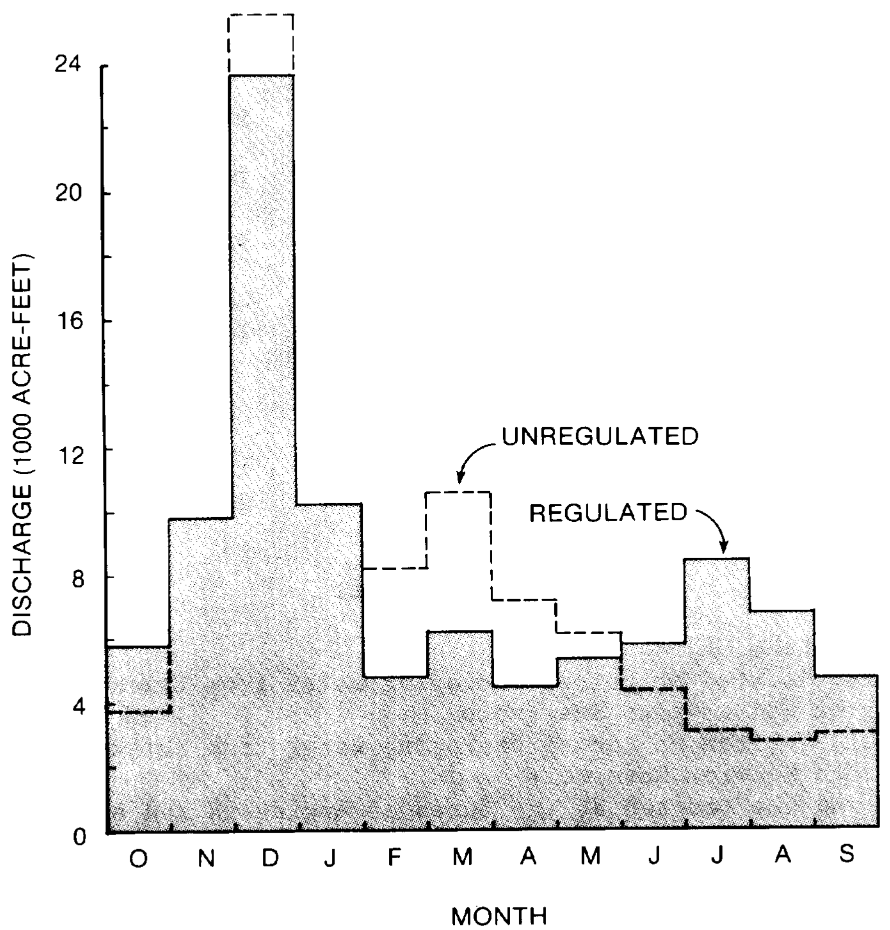

Figure M-19. Monthly discharge of the Sacramento River at Bend Bridge (near Redding), regulated and unregulated, water year 1984.

TABLE M-7
Major Hydropower Projects in the Central
Valley Project Multiple-Purpose Reservoir System

Project	River	Owner or Operator	Reservoir Functions	Conservation Storage (1000 AF)	Installed Capacity (MW)
Trinity 2/	Trinity	USBR	FIPR 1/	2,285	128
Lewiston	Trinity	USBR	IP	pondage	-
Francis Carr	3/	USBR	P	pondage	154
Whiskeytown	Clear	USBR	IP	214	-
Spring Creek	4/	USBR	P	pondage	190
Shasta	Sacramento	USBR	FIPNRWS	4,050	573
Keswick	Sacramento	USBR	FPR	pondage	90
Folsom	American	USBR 5/	FIPRWS	921	210
Nimbus 6/	American	USBR	FRP	pondage	15
New Melones	Stanislaus	USBR 5/	FIPRWS	2,090	392
O'Neill 7/	San Luis	USBR	IPRS	pondage	25
San Luis	San Luis	USBR	IPRS	1,961	424
Totals				11,521	2,201

1/ reservoir purposes: F - flood control
I - irrigation
P - hydropower
N - navigation
R - recreation
W - fish and wildlife
S - water supply

2/ Clair Engle Lake

3/ powerplant, located on tunnel conveying water from Lewiston Reservoir to Whiskeytown Reservoir

4/ powerplant, located on tunnel conveying water from Whiskeytown Reservoir to Keswick Reservoir

5/ designed and constructed by the Corps of Engineers and operated by the Bureau of Reclamation

6/ reregulating reservoir for Folsom powerplant

7/ reregulating reservoir for San Luis pumping-generating plant

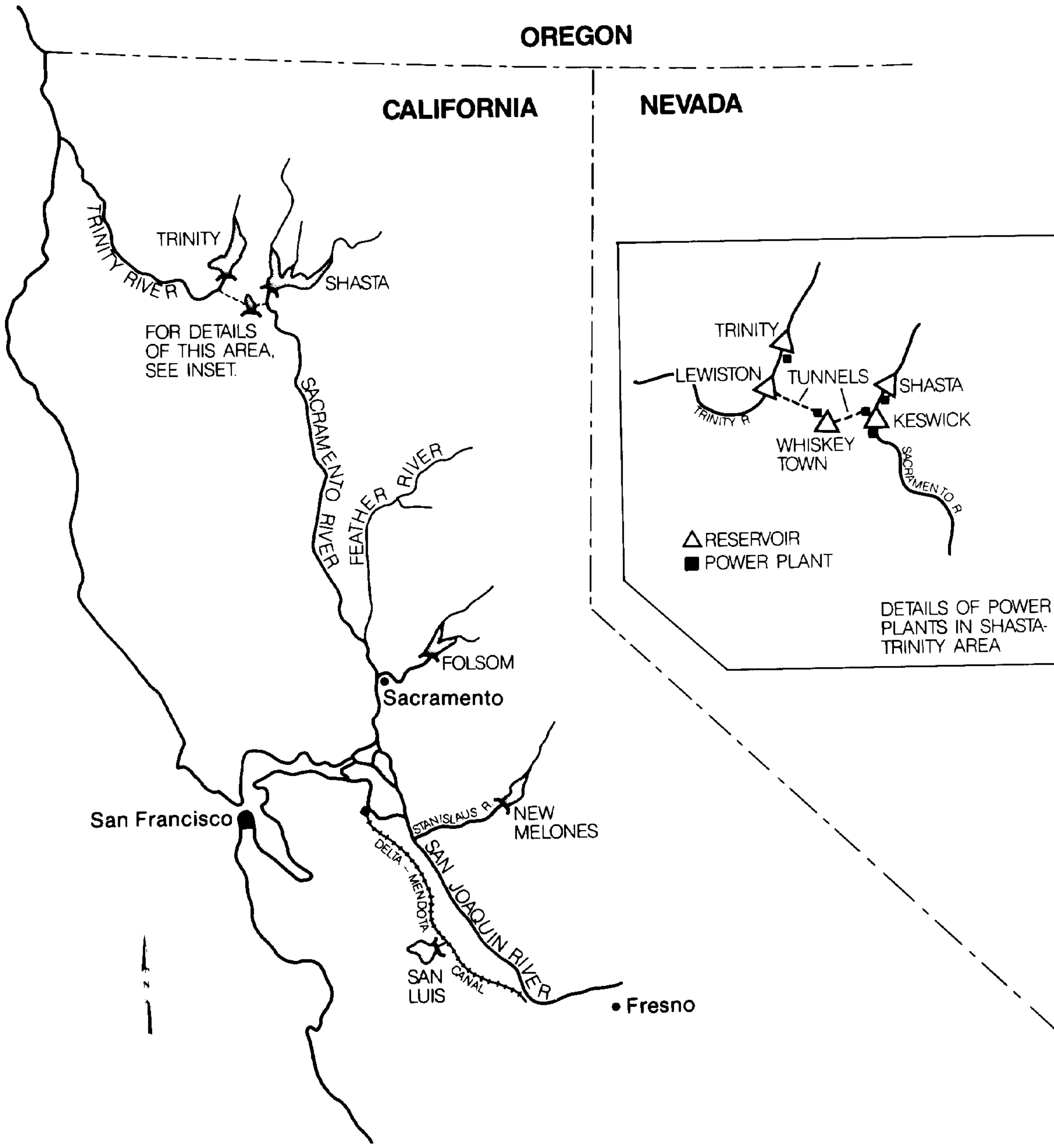

Figure M-20. Major hydropower components of the Central Valley Project, California

(3) The Project consists of seven major storage projects, together with 11 smaller reservoirs for regulation and power generation, 39 pumping plants, and more than 500 miles of canals (see Figure M-20 and Table M-7). Water is stored in the high runoff winter and spring months to meet irrigation requirements, which are greatest during the summer months (see Figure M-21). The extensive system of canals and pumping plants is used to transfer water from the water-rich Sacramento River basin in the north to the water-poor, but intensively cultivated, San Joaquin Valley in the south. The overall project was designed and operated by the Bureau of Reclamation. Most of the reservoirs and other project elements were constructed by the Bureau of Reclamation, but the Folsom and New Melones reservoirs were constructed by the Corps of Engineers. The Bureau of Reclamation has overall responsibility for operating the Central Valley Project.

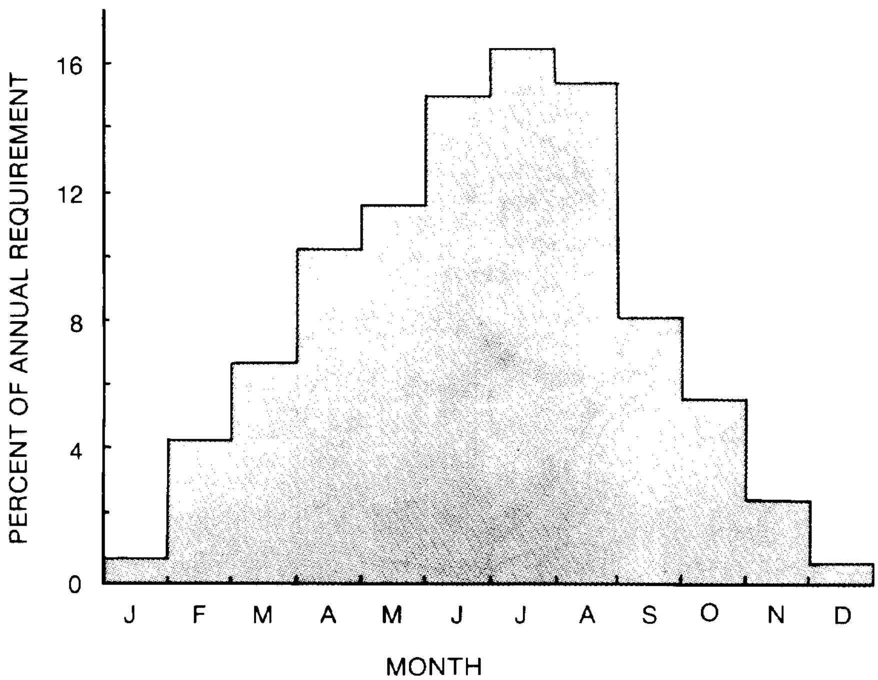

Figure M-21. Typical seasonal distribution of irrigation requirements, Central Valley Project

(4) The key storage projects are Trinity (Clair Engle Lake) and Shasta in the north and Folsom and New Melones in the central portion of the basin. San Luis is a large seasonal pumped-storage reservoir that is used to control flow through the Delta-Mendota and San Luis canals. Millertown provides water for the upper San Joaquin Valley. The volumes in parentheses represent usable storage.

b. Storage Regulation.

(1) Reservoir storage is divided into two zones. The upper zone is a joint use storage zone, which is regulated for flood control in the winter months and irrigation and power in the summer and fall months. Below this is a carryover storage zone, which is used to meet irrigation and power requirements in periods of extended droughts. About 30 percent of the usable storage space in the major reservoirs is allocated to joint use storage and the remaining 70 percent to carryover storage.

(2) Because of the differences in the runoff patterns in various parts of the basin, drafting of the individual reservoirs follows somewhat different operating schedules. For this reason, the easiest way to describe system operation is to begin about the first of October, following the end of the irrigation season, when the reservoirs are at their lowest elevations. Refill takes place in the winter and spring months, but it is constrained to some extent by flood control requirements. Water is required for irrigation the year around, but the bulk of the demand occurs from May through August (see Figure M-21).

(3) Much of the runoff in the basin comes from rainfall. Shasta, for example, is regulated almost exclusively to control rainfall runoff. A fixed flood control requirement is maintained through the first of January. Filling of the joint use storage begins at that date, following statistically derived rule curves which are designed to insure as great a probability of refill as possible while still maintaining flood control requirements through 1 February. Refill of Shasta is usually completed about the first of May.

(4) By way of contrast, the drainage area above New Melones is at a higher elevation, and most of the runoff is from snowmelt. Winter and early spring drafts are based on snowpack forecasts, thus permitting deeper drafts and greater power generation in high runoff years. Refill of New Melones is usually not complete until mid-July. For the other storage projects, runoff comes from both rainfall and snowmelt, and provision of flood control space and scheduling of refill are based on a combination of statistically derived refill curves and snowmelt forecasts.

(5) Figure M-22 shows the combined seasonal allocation of storage for the five major reservoirs (Trinity, Shasta, Folsom, New Melones, and San Luis). The figure shows how the refill schedule can vary, depending on the prevailing water conditions. Also plotted on Figure M-22 is the actual operation for water year 1984.

(6) A large part of the irrigated land in the San Joaquin Valley is served by the Delta-Mendota Canal. The canal originates in the Sacramento-San Joaquin River delta area ("the Delta") and extends in a southeasterly direction, generally parallel to the San Joaquin River, for about 115 miles, terminating about 30 miles west of Fresno. Although the irrigation demand occurs primarily in the summer months, water is pumped into the canal from the Delta the year around. Water excess to irrigation needs is pumped into the San Luis Reservoir, to be held until the peak irrigation demand season, when it is released back into the Delta-Mendota and San Luis Canals. A portion of the San Luis storage is also allocated to the state-operated California Water Project, with water being pumped from and discharged back into the California Aqueduct, which runs generally parallel to the CVP's Delta-Mendota Canal.

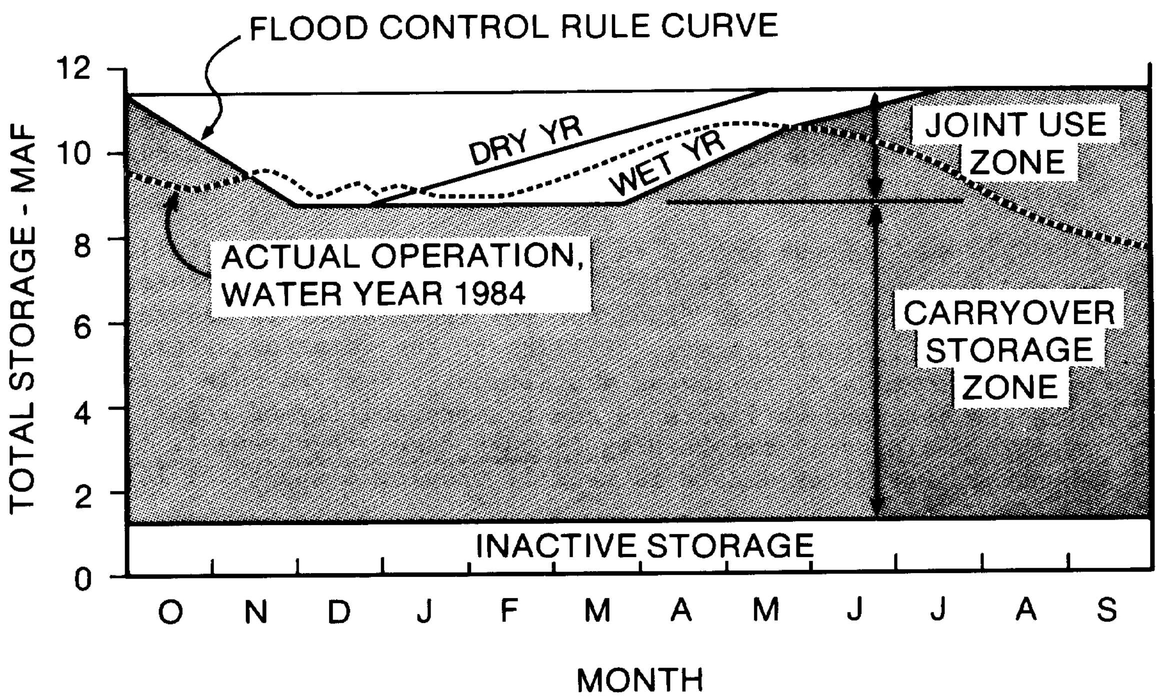

Figure M-22. Seasonal storage allocation, Central Valley Project, showing actual operation in water year 1984

(7) The San Luis Reservoir is one of the few examples of a seasonal pumped-storage plant located in the United States. Pumping is accomplished in periods of low power demand, when the cost of pumping energy is relatively low. Most of the releases are made during high demand periods, when the value of the generation is high.

(8) The water pumped from the Delta is a mix of natural runoff and releases from storage projects such as Trinity and Shasta. Minimum flows must be maintained within the Delta in order to prevent salt water intrusion, so a portion of the storage releases is allocated to meet this requirement.

(9) Recreational use of the Shasta and Folsom reservoirs is much higher than the other projects, so the sequence of draft from the various reservoirs is scheduled recognizing that it is desirable to maintain Shasta and Folsom as high as possible through Labor Day. This draft sequence insures that irrigation requirements are met, but it may be less than optimal from the standpoint of power generation.

(10) The hydropower plants of the CVP provide a dependable capacity of 800 to 1000 megawatts to the Pacific Gas and Electric Company (PG&E). Contracts with PG&E specify minimum 12-month, 6-month, and monthly energy delivery and provide benefits for exceeding these levels. The USBR submits a daily generating schedule which is based upon CVP reservoir conditions to PG&E, which dispatches this energy on an hour-by-hour basis to minimize system fuel costs.

c. Critical Period.

(1) The firm water yield of the system is based on the critical period 1928 through 1934. The reservoirs can meet about 80 percent of the CVP's irrigation water requirements during that period. During adverse water years, the farmers can supplement their CVP water supply with groundwater pumping. In years of plentiful water supply, the additional water can be used for increasing crop production or to recharge the ground water supply.

(2) The system's firm power output is also based on the 1928-34 critical period. A portion of the firm power is used to meet CVP pumping requirements, and the remainder is sold to local electric power utilities. The most effective use of hydropower in the local power systems is as peaking power, and the CVP hydro plants were sized to deliver dependable capacity supported by sufficient firm energy to permit them to operate at an annual plant factor of about 25 percent. In good water years, additional energy is also available, and this is marketed on a month-by-month basis, depending on forecasted runoff, reservoir levels, irrigation requirements, and other factors.

d. System Management. Operation of the Central Valley Project is the responsibilty of the Mid-Pacific Region, Bureau of Reclamation, 2800 Cottage Way, Sacramento, CA 95825.

e. Summary.

(1) The major project functions served by the CVP reservoirs (irrigation, flood control, and power generation) are generally compatible. Flood control space is maintained in the winter months, and the reservoirs are allowed to fill in the spring to provide storage for summer and fall irrigation releases. However, because a large portion of the spring runoff is from rainfall and cannot be predicted, maintaining winter flood control space sometimes results in joint use storage not refilling completely. Carryover storage is provided for years when joint use storage does not refill. Power is generated primarily from storage releases for irrigation. However, because a substantial portion of the power generation is used for summer irrigation pumping and because the remainder is used in summer-peaking power systems, this schedule conforms reasonably closely to the power demand pattern. Power exchange agreements with local utilities and the seasonal pumped-storage operation at San Luis provide additional flexibility in helping to optimize the use of CVP power generation.

(2) In adverse years, storage is regulated to maximize firm yield for irrigation and firm energy to meet CVP pumping requirements and dependable capacity sales contracts with utilities. In good water years, the additional runoff is regulated to maximize irrigation benefits and power revenues.

(3) Other water uses also affect reservoir operation. Storage releases above irrigation and power requirements must be made at times in order to meet in-stream flow requirements for fish and wildlife and to prevent salinity intrusion in the Sacramento River delta. Heavy recreational use of certain reservoirs in the summer months affects the sequence of storage drafts among the various reservoirs. Navigation requirements on the Sacramento River can generally be met with releases for other purposes.

M-8. Columbia River System.

a. General.

(1) The Columbia River drains an area of approximately 259,000 square miles in seven western states and British Columbia. This large basin includes vastly different climates and topography. Peak runoff occurs during the spring months and is largely a result of

snowmelt in the high interior mountains east of the Cascades (Figure M-23). Only fifteen percent of the Columbia River basin lies in British Columbia, but this region contributes forty percent of the river's average annual runoff at The Dalles (a key gaging station located downstream of most of the basin's hydropower facilities).

(2) More than 250 reservoirs and over 100 hydroelectric projects are located within the Columbia River Basin and adjacent coastal river basins. However, this discussion will be limited to the projects of the coordinated Columbia River System. About 75 projects, almost all of which have power generating facilities, are included in this system. The seasonal storage in the system is operated primarily for flood control and power generation, but some of the projects serve other purposes as well, including navigation, irrigation, fish and wildlife, and recreation. The total usable

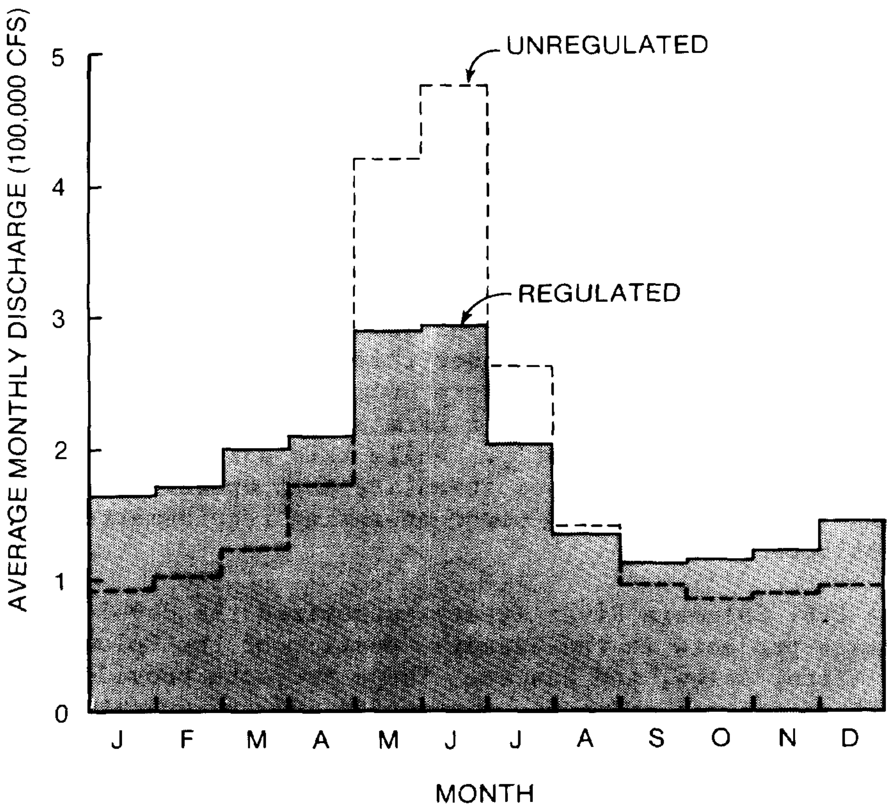

Figure M-23. Average monthly discharge of the Columbia River at The Dalles, Oregon, regulated and unregulated, based on historical streamflows for the period 1928-1978 reservoir storage available to the system (excluding projects located on tributaries below The Dalles Dam and in coastal river basins) is about 42 million acre feet, or about 30 percent of the average annual runoff of the Columbia River at The Dalles.

(3) Some of the projects in the coordinated system are owned by utility companies, but many of the key projects were constructed by the Corps of Engineers and the Bureau of Reclamation. Power generation from the Corps and Bureau projects is marketed by the Bonneville Power Administration (BPA). Three of the major headwater storage projects are located in Canada and are operated by the British Columbia Hydro and Power Authority (BC Hydro). Figure M-24 shows the major projects in the coordinated system, and Table M-7 lists the characteristics of those and other important projects.

b. The Coordinated System.

(1) The term "Coordinated Columbia River System" is used in this section to describe the projects operated under three separate but interrelated operating arrangements: (a) the Pacific Northwest Coordination Agreement, (b) the Columbia River Treaty, and (c) the statuatory flood control responsibilities of the Corps of Engineers. Not all of the projects in the system are covered by all three arrangements and authorities.

(2) The Pacific Northwest Coordination Agreement (PNCA) is a contract among the utility companies operating hydropower plants on the Columbia River and major tributaries and three Federal agencies (the Corps, the Bureau, and BPA). Under this agreement, the seasonal power storage is regulated as if it were under a single ownership. This results in a substantially larger firm power output than if the projects were operated independently. While this agreement does not govern non-power functions, it does stipulate that operation for power will not jeopardize the non-power operating requirements of individual projects.

(3) The 1961 Columbia River Treaty authorized the development of three storage projects in the Canadian portion of the Columbia River Basin: Mica, Arrow, and Duncan. These projects provide storage for flood control and power generation and are operated for the joint benefit of the United States and Canada. The Treaty also permitted the United States to construct the Libby reservoir to its optimum elevation, which required that the reservoir extend into Canada. The British Columbia Hydro and Power Authority constructed and operates the Mica, Arrow, and Duncan projects and is the Canadian member of the reservoir management team. The United States is represented by the Corps (flood control aspects) and BPA (power

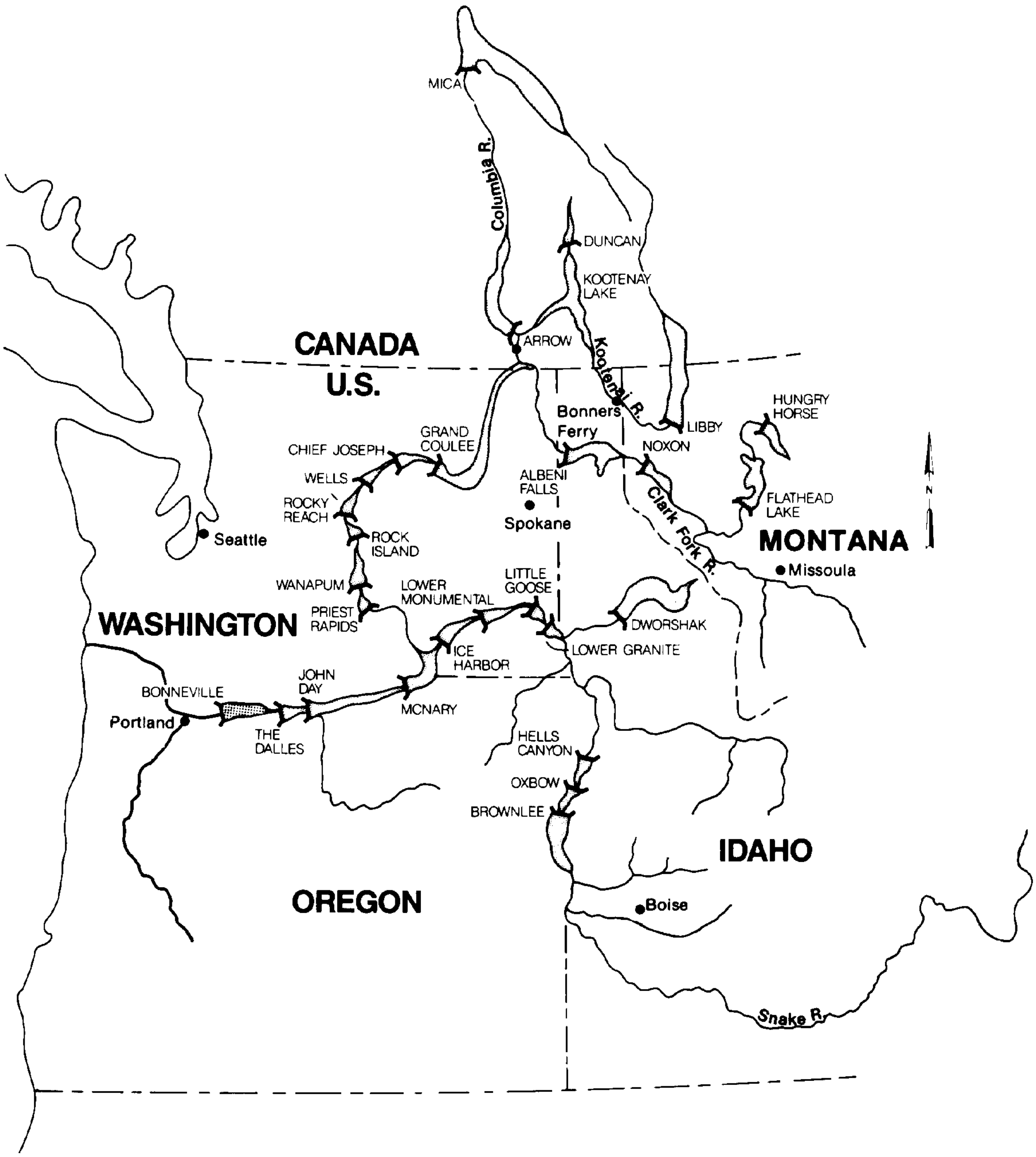

Figure M-24. Major projects in the Coordinated Columbia River system

TABLE M-7
Major Projects in the Coordinated Columbia River System

Dam	River	Owner or Operator 2/	Reservoir Functions 3/	Conservation Storage (1000 AF)	Inst. Cap'y (MW)
Columbia Mainstem System 1/					
Mica	Columbia	BC Hydro	FP 3/	12,000 4/	1,740 5/
Arrow	Columbia	BC Hydro	FP	7,100	--
Libby	Kootenai	Corps	FPR	4,980	525
Duncan	Duncan	BC Hydro	FP	1,399	--
Hungry Horse	N.Fk.Flathead	USBR	FPR	3,161	285
Kerr	Flathead	MPCo.	FPR	1,219	168
Noxon Rapids	Clark Fork	WWPCo.	P	231	397
Cabinet Gorge	Clark Fork	WWPCo.	P	pondage	200
Albeni Falls	Pend Oreille	Corps	FPR	1,155	43
Boundary	Pend Oreille	Seattle	P	pondage	635
Grand Coulee	Columbia	USBR	FIPR	5,185	6,580
Chief Joseph	Columbia	Corps	IPR	pondage	2,069
Wells	Columbia	Douglas	PR	pondage	774
Chelan	Chelan	Chelan	PR	677	48
Rocky Reach	Columbia	Chelan	PR	pondage	1,212
Rock Island	Columbia	Chelan	P	pondage	620
Wanapum	Columbia	Grant	PR	pondage	831
Priest Rapids	Columbia	Grant	PR	pondage	788
Brownlee	Snake	IPCo.	FP	980	585
Oxbow	Snake	IPCo.	P	pondage	190
Hells Canyon	Snake	IPCo.	P	pondage	392
Dworshak	N. Clearwater	Corps	FNPR	2,016	400
Lower Granite	Snake	Corps	INPR	pondage	810
Little Goose	Snake	Corps	INPR	pondage	810
Lwr. Monument.	Snake	Corps	INPR	pondage	810
Ice Harbor	Snake	Corps	INPR	pondage	603
McNary	Columbia	Corps	INPR	pondage	980
John Day	Columbia	Corps	FINPR	535 6/	2,160
The Dalles	Columbia	Corps	NPR	pondage	1,807
Bonneville	Columbia	Corps	NPR	pondage	1,077
Other projects	--	--	--	1,395	598
Subtotal				42,033	26,397
West Slope Projects (34) 7/				5,561	2,755
Total				47,594	29,480

TABLE M-7 (continued)

1/ major projects in the Columbia River Basin above Bonneville Dam (but excluding projects in the Snake River subbasin above Brownlee). Operation of these projects is described in Section M-8c.

2/ abbreviations:

BC Hydro -	British Columbia Hydro and Power Authority
Corps -	Corps of Engineers
USBR -	U.S. Bureau of Reclamation
MPCo. -	Montana Power Company
WWPCo. -	Washington Water Power Company
Seattle -	Seattle City Light
Douglas -	Douglas County Public Utility District
Chelan -	Chelan County Public Utility District
Grant -	Grant County Public Utility District
IPCo. -	Idaho Power Company

3/ reservoir functions:

F - flood control
I - irrigation
N - navigation
P - hydropower
R - recreation
W - fish and wildlife
S - water supply

4/ of which only 7,000,000 AF is operated under the terms of the Columbia River Treaty
5/ not included in the total generation (U.S. projects only)
6/ flood control storage, only pondage is available for power operations.
7/ projects on tributaries of the Columbia River below Bonneville dam and other projects in western Oregon and Washington. Operation of these projects is described in Section M-8g.

aspects). The Pacific Northwest Coordination Agreement ensures that the expected power benefits from the regulation of the Treaty projects are in fact realized in the United States.

(4) The storage projects constructed by the Corps of Engineers and the Bureau of Reclamation include flood control as an authorized purpose, and a number of the non-Federal hydro projects are required under terms of their license to provide flood control storage space.

The Corps of Engineers has responsibility for the flood control regulation of all of these projects. This regulation is accomplished on a coordinated basin-wide basis. The flood control regulation of the Canadian Treaty projects is included in this operation as well.

(5) A number of other operations are also involved in the regulation of the Coordinated Columbia River System. For example, storage drafts and spill are required at some projects to enhance the downstream migration of salmon and steelhead smolts. Navigation channels must be maintained on the Columbia River from the mouth to its confluence with the Snake River and on the Snake as far as Lewiston, Idaho. A number of irrigation projects draw water from the Columbia and certain tributaries, and this must be accounted for in system operation. There are also other operating agreements involving power, including an arrangement to coordinate the power operation of the seven mainstem projects (Grand Coulee through Priest Rapids) on a real-time basis. The generation from these projects is controlled by a diverse group of utilities and Federal agencies.

c. System Operation.

(1) The two dominant functions served by the reservoir system are power generation and flood control. The maximum runoff occurs in the late spring and early summer, while natural flows are relatively low from August through early April. The power demand is relatively uniform throughout the year, but reaches a peak in the winter months (Chapter 2, Figure 2-2). Thus, from the standpoint of power generation, the objective is to store snowmelt runoff in the spring and early summer months for release in the remaining months, with the highest firm storage releases in the winter months (see Figure M-23). This operation is generally compatible with flood control requirements, because the primary objective of the flood control operation is to reduce the peak of the spring freshet in order to provide protection for the intensively developed reach of the Columbia River below Bonneville Dam. Flood protection is also provided to local areas within the basin.

(2) The seasonal operation of the reservoirs is defined by a series of rule curves, which are developed at the start of each operating year and updated as the year progresses. The operating year can be divided into three seasons:

- August through December: the fixed drawdown period. No runoff forecast data is available, so the system operates in accordance with fixed rule curves.

- January through March: the variable drawdown period. Runoff forecasts are available, and the reservoirs are drafted at a rate that provides an adequate level of flood control, meets firm energy requirements, and generates as much additional energy as possible while maintaining a high assurance of refill.

- April through July: the refill season. The reservoirs store the spring runoff using the same basic operating criteria as applied in the January-March period.

(3) Prior to each operating year, period-of-record sequential streamflow routing studies are made to (a) identify the critical period, (b) determine the system's firm energy load-carrying capability, and (c) derive rule curves for defining the operation of individual projects. These parameters can vary from year to year depending on system load requirements, thermal generation available to the system, non-power operating constraints, and other factors. For example, with the storage presently available to the system, firm energy is usually defined by the 42-month critical drawdown period, September 1928 through February 1932, but under some circumstances, the 20-1/2 month period, August 1943 through mid-April 1945, controls.

(4) Once the basic operating parameters described in the preceding paragraph have been defined, the actual operation of the system over the course of a year is based on balancing three related but sometimes conflicting driving functions:

- providing adequate flood storage space for control of the spring runoff
- maximizing power generation
- maintaining a high probability of reservoir refill.

In the fixed drawdown period (August-December), forecasts are not available, so reservoir operation is guided by three fixed rule curves. These are the critical rule curve, the assured refill curve, and the mandatory rule curve (see Figure M-25). The critical rule curve (CRC) defines the reservoir elevations that must be maintained to ensure that firm energy requirements can be met under the most adverse historical streamflow conditions. Critical rule curves are derived for all four years in the critical period. If the system begins the operating year full, the CRC is based on the drawdown schedule for the first year in the critical period. The assured refill curve (ARC) defines the elevations that must be maintained to ensure refill if the third lowest historical water year should occur. The mandatory (or flood control) rule curve (MRC) defines the drawdown required to ensure that some flood control space has been evacuated by the time the first runoff forecasts become available.

(5) On the first of January, the first runoff forecast becomes available. At this point, it becomes possible to define some additional curves. The variable refill curve (VRC) is used to limit secondary generation and defines the minimum reservoir elevations to ensure refill of the reservoir by the end of July within a 95 percent probability. The runoff forecast also permits definition of the system flood control requirements, which in turn establishes a forecast-based MRC. New runoff forecasts are prepared monthly through June, and the VRC and MRC are revised to reflect the new data. In January, February, and March, an additional curve is defined: the lower limit energy contract curve (LLECC). This curve

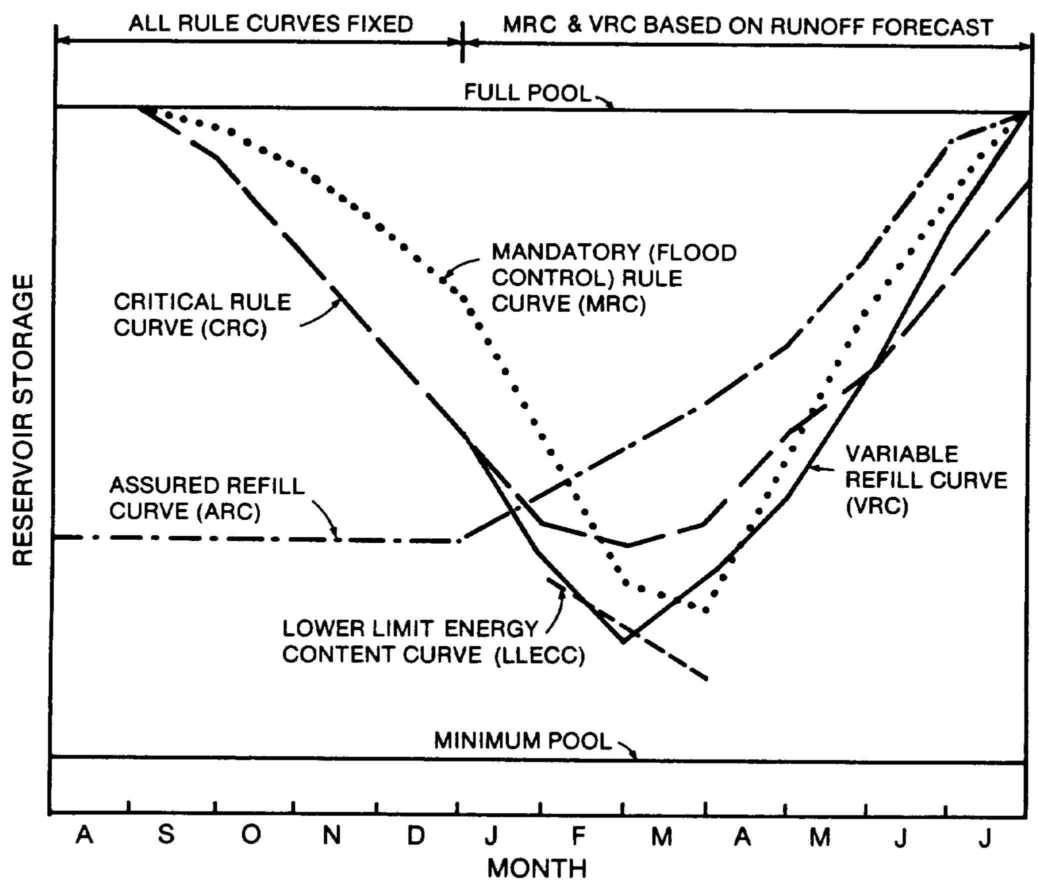

Figure M-25. Basic rule curves for typical Columbia River basin storage project for given operating year is based on a reverse routing for the most severe single late runoff water year, and it establishes a limit on draft in order to protect the system's ability to meet firm loads until the start of the spring runoff.

(6) The firm energy output of the hydro system represents the amount of energy that the system is obligated to supply. Regional power resource planning is based on the hydro system's firm energy capability. In most years, however, additional energy (secondary energy) is available. This energy is available for displacing thermal generation in the Pacific Northwest and for export to the Pacific Southwest. The primary strategy for maximizing secondary energy production is to draft as much storage as is practical in the winter months. An operating rule curve is developed to define the minimum levels to which a reservoir can be drafted while serving secondary loads without jeopardizing refill or firm energy production in either the current year or in subsequent years.

(7) The operating rule curve (ORC) is a composite curve based on the controlling rule curve for each time period, and is defined as follows:

- August-December: the higher of the ARC or the CRC, unless the MRC is lower, in which case it controls.
- January-March: the same as for August-December, unless the VRC is lower, in which case it controls. In no case can the ORC be lower than the LLECC, however.
- April-July: the same as for January-March except that the LLECC consideration does not apply.

Figure M-26 shows derivation of the operating rule curve (ORC) for a typical year based on the various rule curves shown on Figure M-25. The ORC defines the normal lower limit to reservoir operation and the MRC (flood control rule curve) defines the upper limit. The darker shaded area represents the normal range of reservoir operation. A project would operate below the normal range of operation only if required to meet firm loads and above the normal range of operation only when regulating floods.

(8) Because the streamflows are typically very low in the late summer and fall months, and because of the uncertainty regarding future runoff, reservoir operation in the August-December period typically follows the ORC quite closely. Sometimes, rainfall storms generate higher flows in the latter portion of this period, but because secondary energy has relatively high value, excess streamflow is usually converted to energy production rather than being stored. If the water supply is good during the period January-March, water in

excess of that required to meet firm energy obligations will either be used for generation or stored between the ORC and the MRC, depending on the current value of secondary energy and the expected future value. As a practical matter, during the runoff season the ORC is usually followed fairly closely. This is because water left in storage above that curve might have to be spilled if the reservoir fills, and its energy potential would be lost.

(9) The preceding paragraph describes operation in a good water year. In a year with a light snowpack, the ARC might define the post-January operating rule curve. However, reservoir operation

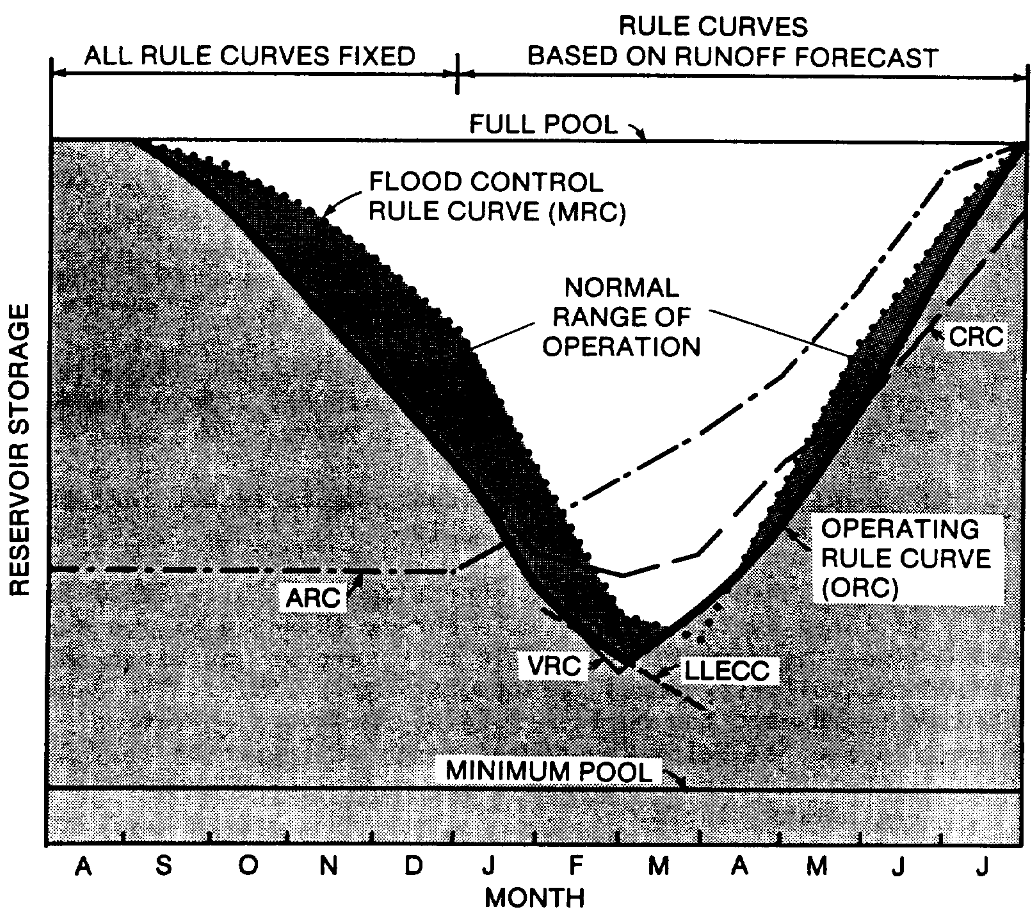

Figure M-26. Operating rule curve for typical Columbia River basin storage project for given operating year would not necessarily follow that curve, because the operating rule curve serves only to define the level below which no secondary energy will be produced. In an adverse year, it may be necessary to draft below the operating rule curve in order to serve firm loads. For example, if the first year of the critical period were to occur, reservoir operation would follow the CRC, which would be substantially lower than the ARC-defined operating rule curve. Over a long period of operation, there could be a number of occasions when it is necessary to draft below the operating rule curve, but this would be done only to meet firm load requirements.

(10) In about one year in four, the runoff is insufficient to permit the reservoir system to refill. If the system fails to fill, generation in subsequent months will be limited to firm energy requirements. The second-, third-, and fourth-year critical rule curves would be used to define reservoir operation in periods of extended drought.

(11) An interesting technique is used to increase system firm energy capability in most years. Firm energy capability is based on a four-year critical period, and the classic approach to reservoir operation would be to design rule curves such that the same amount of firm energy could be produced in all four years. However, the probability of having two or more adverse streamflow years in a row is low. Recognizing this low probability, the system rule curves are designed to produce more firm energy in the first year of the critical period than in the last three years. Thus, in years when the reservoir system fills (about three years out of four), the system is able to produce the higher level of firm energy output. In those years when the reservoir system fails to fill, the system's firm energy capability would be lower. The region's utilities believe that the benefits achieved by increasing firm capability in most years exceed the liabilities incurred in those years when the system does not refill and must operate at a reduced firm capability.

(12) The Columbia River system consists of a complex network of parallel and tandem reservoirs, with some run-of-river projects (with pondage) situated between reservoirs and other pondage projects located downstream of the entire reservoir system. The project rule curves are based on a system approach to determining the sequence of storage draft from individual reservoirs. The overall objective is to draft first from those reservoirs where the amount of energy produced (both at-site and downstream) is large compared to the loss in energy in subsequent months due to reduced head at-site (as a result of the draft). This is the "storage effectiveness" approach described in Section 5-14 of Chapter 5. Basing system operation exclusively on storage effectiveness would result in near-optimum power generation. However, other factors must also be considered in

defining the operation of both the system and individual projects. These factors include (a) flood control operation requirements, (b) minimum flow requirements for non-power purposes, (c) reservoir recreation considerations (which encourage equal drawdown to keep all reservoirs relatively high), (d) fish and wildlife requirements, (e) the requirements of the Columbia River Treaty, and (f) the specific requirements of individual project owners. System operation is therefore designed to produce as much power as possible within these constraints.

d. Other River Uses.

(1) Releases for power generation and flood control are generally adequate to maintain navigation on the lower Snake and lower Columbia Rivers. During the growing season, regulated flows on the mainstream Columbia and lower Snake are usually sufficient to meet irrigation requirements. Only at Grand Coulee and on some of the tributaries does irrigation influence reservoir operation.

(2) High flows must be maintained in the late spring for successful downstream fish migration. In above average years this can usually be accomplished without special regulation, but in low runoff years, operation to maximize power would result in too little water being released in the spring months to maintain adequate flows for downstream fish passage. Hence, some reservoir storage (called "water budget" storage) is reserved until the spring to insure that downstream fish passage requirements can be met.

(3) Reservoir recreation is generally compatible with the basic power-flood control regulation in that the reservoirs are maintained at their highest levels during the summer recreation season. However, in some years, the reservoirs either fail to fill, or below normal flows in late summer cause them to draft early, and the resulting lower reservoir elevations adversely affect reservoir recreation.

e. Hourly Power Operation.

(1) The preceding discussion applies primarily to the seasonal power operation of the Columbia River reservoir system. As of operating year 1985-86, hydro generation met about three-quarters of the region's firm energy requirements and system peaking capability. The remaining resources are primarily new base load nuclear and coal-fired steam plants. Accordingly, hydro meets almost all of the variable portion of the daily load (peaking and intermediate), as well as a large portion of the base load. Thermal plants carry the balance of the base load. Depending on their respective installed capacities, non-power operating restrictions, and flow character-

istics, individual hydro plants may be operated to meet peaking, intermediate, or base load requirements, or combinations thereof.

(2) The Pacific Northwest Coordination Agreement deals with the seasonal coordination of storage operation. Each individual utility handles its own short-term load dispatching. However, for adjacent hydro projects to be utilized effectively, their operation must be coordinated on at least an hourly basis. About two-thirds of the region's hydro capacity belongs to the Federal government (the Corps of Engineers and the Bureau of Reclamation), and these projects are dispatched on a coordinated basis by the Bonneville Power Administration. Most of the larger projects are on automatic generation control. BPA's main dispatch center coordinates the hourly operation of the chain of eight projects on the lower Snake and lower Columbia Rivers (Lower Granite through Bonneville). The other major continuously developed reach is the seven-project system on the middle Columbia River from Grand Coulee through Priest Rapids. These projects are owned by several different entities but are operated together under a special hourly coordination agreement. Most of the remaining intensively developed reaches are under the control of a single utility or agency.

f. Critical Period. The system's firm energy load carrying capability is defined by the 42-month critical drawdown period, September 1928 through February 1932. Under some combinations of system loads, resources, and other factors, the 20-month critical drawdown period, August 1943 through mid-April 1945, controls.

g. West-Slope Projects.

(1) The above discussion applies to the portion of the Columbia River basin above Bonneville Dam, which contains about 90 percent of the region's hydropower capability. The remaining projects are located on streams draining the west slopes of the Cascade Mountains or in coastal river basins. While these projects are operated as part of the Pacific Northwest Coordination Agreement, these streams have a different hydrologic pattern than the mainstream Columbia, and project operation follows a somewhat different pattern.

(2) Like the eastern portion of the Columbia River Basin, the bulk of the precipitation falls in the winter months. However, most of it occurs as rainfall rather than snow. Thus, natural streamflows are highest in the winter months and are normally quite low in the summer and early fall months.

(3) This runoff pattern fits the regional power demand pattern quite closely. However, operation for power conflicts somewhat with flood control requirements. Six of the hydro projects located on the

western slopes of the Cascade Mountains are Corps of Engineers multiple-purpose projects, which include flood control as a major purpose. Some of the non-Federal hydro projects in this part of the region also provide seasonal flood control storage.

(3) In order to meet the combined requirements of flood control, hydropower, and low flow augmentation in the late summer and early fall, the Corps projects are operated in accordance with a seasonal rule curve similar to that shown in Figure M-27. The storage is divided into three zones: (a) a small amount of exclusive flood control space on top, to protect against summer floods, (b) a large joint-use storage zone, and (c) a small exclusive power storage zone on the bottom, to help meet firm power requirements in dry winters.

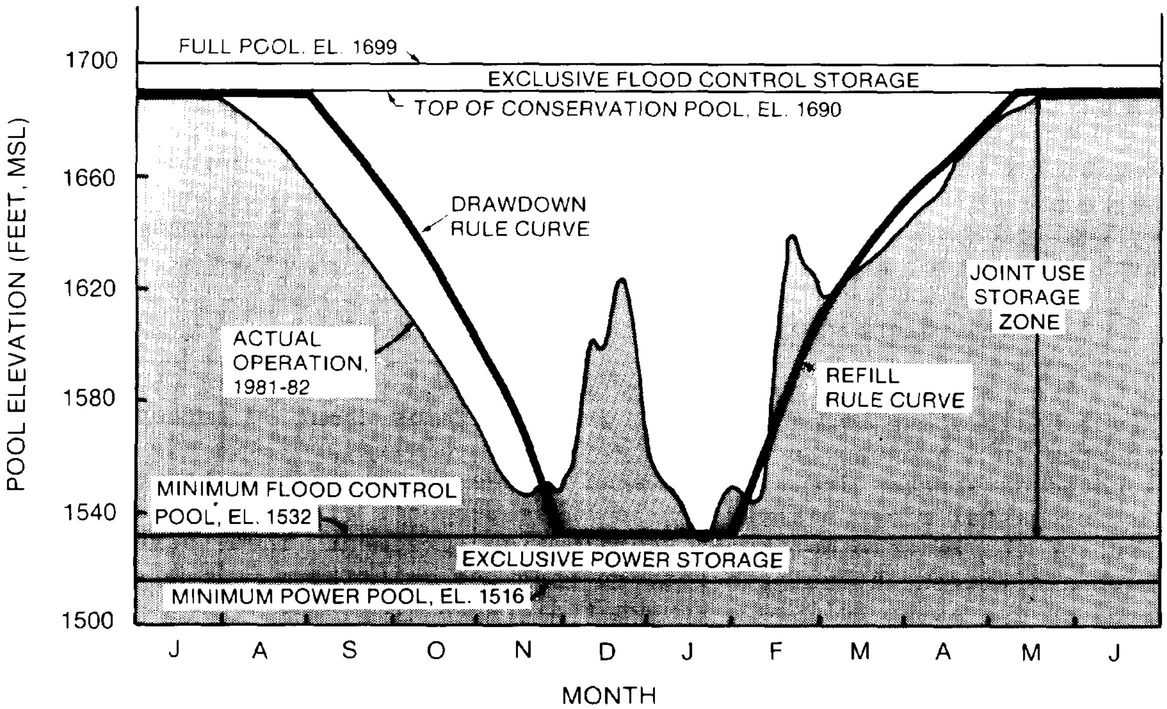

Figure M-27. Rule curve for Cougar Reservoir, a multiple-purpose project located in the western portion of the Columbia River basin, showing actual operation during the year 1981-1982

(4) Reservoirs are maintained at low levels during the winter months to provide maximum space for controlling rainfall-generated floods. Although flows are typically high in these months, the reduced head lessens generating capability. As the probability of flooding diminishes, the reservoirs are allowed to refill starting on 1 February, with the objective of filling the joint-use storage by about 1 June. Drafts are made through the summer and fall months for hydropower, irrigation, and low-flow augmentation for navigation, fish and wildlife, and other purposes. Additional drafts are made if necessary to insure that the winter flood control pool elevation is reached by 1 December.

(5) The utility-owned hydro storage projects located west of the Cascade Mountains are operated in accordance with power rule curves. However, because runoff is not forecastable, some of the curves shown on Figure M-25 do not apply (specifically, the VRC and LLECC). The CRC defines the lowest level to which a reservoir will be drafted in each period to meet secondary loads. Most of these reservoirs are annual reservoirs (operating on an annual cycle), and are completely drafted and refilled in every year. Some utility-owned projects provide seasonal flood control storage and thus have a mandatory rule curve (MRC).

h. System Management. Seasonal regulation of the hydro system is controlled by the 18-party Pacific Northwest Coordination Agreement and the Columbia River Treaty with Canada. Project operation within limits imposed by these agreements is controlled by the individual project owners. Overall responsibility for the operational management of the Federal hydro projects to meet multiple-purpose objectives belongs to the Corps of Engineers (North Pacific Division, PO Box 2870, Portland, OR 97208), and the Bureau of Reclamation (Pacific Northwest Region, PO Box 043, 550 West Fort Street, Boise, ID 83724). The Bonneville Power Administration (PO Box 3621, Portland, OR 97208), directs the power operation of the Federal projects within limits established by the Corps and the Bureau of Reclamation. Flood control operation of both Federal and non-Federal projects is monitored by the Corps of Engineers.

i. Summary.

(1) The Columbia River reservoir system provides about 42 MAF of usable storage, which is equivalent to about 30 percent of the average annual runoff at The Dalles. The bulk of the reservoir storage in the system is joint-use storage, regulated primarily for hydropower and flood control, although other river uses, such as irrigation, recreation, and fish and wildlife, also influence the operation of individual projects, as well as the system. The river is primarily a snowmelt stream, experiencing high runoff in the late spring and early summer and relatively low flows during the remainder

of the year. The seasonal power demand pattern is the reverse of the runoff patterns, with the peak power requirements occuring in the winter months.

(2) The reservoir storage is drafted from late summer through early spring to generate power and provide flood control space. Reservoirs refill in the late spring and early summer. The runoff is, in part, forecastable because it is snowmelt-based. The amount of storage drafted varies from year to year, depending on the loads and the amount of runoff expected. Reservoir operation is controlled by a series of rule curves based on firm power, flood control, fish and wildlife, and refill requirements, and these curves are adjusted during the operating year as runoff forecast data becomes available. Power operation is designed not only to insure that firm energy requirements are met, but also to produce as much secondary energy as possible without jeopardizing reservoir refill. Secondary energy is used for serving a portion of the region's electroprocess industry loads and for thermal energy displacement both within the region and in the Pacific Southwest.

(3) Hydropower is the predominant source of power in the Pacific Northwest, meeting about two-thirds of the region's firm energy requirement and three-quarters of its peaking requirements. Hydropower carries almost all of the variable portion of the daily load, as well as a large portion of the base load. Although the region's hydro projects are owned by a number of entities, seasonal operation of the system is coordinated through a series of operating agreements, including a treaty with Canada.